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Reviewer(s):	Richard van Leeuwen (SAX), Patryk Chaja (IMP)
Author/editor:	Gerwin Hoogsteen (UT)
Contributing partners:	Universiteit Twente (UT), Saxion University of Applied Sciences (SAX)

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Contributors

Partner no.	Partner short name	Name of the Contributor	E-mail
7	UT	Gerwin Hoogsteen	g.hoogsteen@utwente.nl
7	UT	Aditya Pappu	a.pappu@utwente.nl
8	SAX	Javier Ferreira Gonzalez	j.ferreiragonzalez@saxion.nl
8	SAX	Richard van Leeuwen	r.p.vanleeuwen@saxion.nl
9	IMP	Patryk Chaja	patryk.chaja@imp.gda.pl

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1 List of Abbreviations

In alphabetical order:

ALPG	Artificial Load Profile Generator
DEMKit	Decentralized Energy Management Kit
DSM	Demand Side Management
EC	Energy Community
EMS	Energy Management System
EV	Electric Vehicle
HEMS	Home Energy Management System
PS	Profile Steering
IECON	IoT Edge Computing for carbon Neutral communities
FIT	Feedback Intervention Theory
DER	Distributed Energy Resources
USEF	Universal Smart Energy Framework
UI	User Interface

2 Executive Summary

This deliverable is focused on modelling and design approaches for semi-autarkic neighbourhoods and the development of energy modii. The former refers to neighbourhoods that are self-providing in their energy supplies and potentially able to supply their own energy needs matched in time, by own generation. The energy modii reflect the status of the grid as a whole, in which clear definitions of different modii allows both energy management systems (EMSs) and end-users to operate the grid within its capacity constraints.

These energy modii may play a key role for the energy transition in the developed world. The integration of more renewable energy sources results in a less stable supply of electrical energy. Furthermore, the ongoing electrification introduces additional stress and congestion in the existing ageing infrastructure. Upgrading all grids is costly and may not be feasible. Instead, this deliverable investigates flexible solutions that allow energy communities to be prepared and adapt to an energy system that may be unable to provide energy due to a lack of renewable energy generation or capacity limits in the infrastructure.

The first step is to design an energy community in different aspects, namely: (i) placing and sizing of microgenerators (e.g., solar panels) and flexible assets (e.g., batteries), (ii) the integration of an intelligent EMS for system integration, and (iii) the interaction with the end-users in such a dynamic system. To this end we present a 5-step methodology for design space exploration utilizing the DEMKit + ALPG tooling framework. This approach starts with modelling a community and validating the base model (steps 1-3). Subsequently the model can be extended with additional assets and technologies. Here, the system interaction is important, i.e., the optimization and sizing of assets need to go hand-in-hand as they affect the effectiveness of each other. Therefore, the toolchain is seen as a decision support tool for experts. This leads to a sensible system design from multiple aspects such as investment costs and carbon emissions. The last step is to enable energy modii to investigate how adaptive the community is to disruptive situations in the main grid, e.g., congestion issues or disconnection.

For this, 4 different energy modii are defined in terms of mathematical formulations. These modes are (i) connected, (ii) congested, (iii) scarcity, and (iv) islanded. These temporal modii provide information about the status of the electricity grid. Subsequently, an EMS can utilize this information to prepare the energy community for both foreseen problems, either predicted or announced (e.g., maintenance) as well as sudden events. Using these modes, devices can be switched off to prioritise others which should remain powered. Furthermore, the same definitions are used on energy dashboards or apps, where tips to end-users can assist them in avoiding outages by e.g., postponing the washing machine.

The proposed methodologies are evaluated via the three Dutch demonstration sites. For the Vriendenerf demonstrator it is shown how the methodology can be used to size batteries and assess the resilience of the community under different modii. For the University of Twente Field Lab, we show how the digital-twin approach is leveraged to allow for feed-back of real data in the modelling process to enhance the control schemes. Also, the impact of user interaction is shown since we found that self-sufficiency was improved from 33% to 71% by smart charging in June 2022. Lastly, we validate the modelling aspect for the Aardehuizen demonstrator, which shows that the presented methodology and energy modii are generic enough for use across various situations.

3 Introduction

There has been an increase in electrification in recent years, thanks to an increase in the installation of Distributed Energy Resources (DER), the proliferation of electric vehicles (EV) and heatpumps (HP). According to IEA estimates, 2022 was a record year for DER additions with the annual capacity amounting to 340 GW globally [WeIEA]. The critical role of DERs in keeping a check on the global temperature rise has galvanized the creation of policies incentivizing increased adoption of DERs. In the Netherlands, the policy of '*salderingsregeling' (net-metering)* has aided in the increased installation of rooftop PV panels [WebGOV]. As per the net-metering scheme, when a household generates more solar energy than it uses at a certain time, the excess is fed back to the grid. At the end of the year, the household receives financial compensation of the annual excess solar energy fed back to the grid. The financial profitability of the net-metering scheme has resulted in a record increase in the installation of PV systems, with around 2 GW of new residential solar capacity installed in 2022 alone [WebPVMag]. Geo-political situations have accelerated the rapid electrification as well. The Russia-Ukraine war has generated a political push amongst EU nations to work on diversifying their energy supply and reducing reliance on Russian oil. As per the REPowerEU plan adopted by the EU in May 2022, EU nations have worked on achieving a record high of 41 GW of installed solar energy and on increasing wind capacity by 16 GW, with 39% of EU electricity coming from renewables [WebEU]. The reduced dependency on fossil fuels, increasing electrification of households, rapid installation of DERs is called the *energy transition*; a transition which is accelerated each day due to political and environmental reasons.

However, this rapid transition has generated its own set of problems for the electric grid. The existing grid was not designed of the ever-increasing bi-directional flows of electricity resulting from the energy transition. DERs create an intermittent peak supply of energy during certain parts of the day while the increasing demand from the electrification leads to scarcity problems in other parts of the day. In Netherlands, the grid has reached its capacity in cities such as Amsterdam and provinces such as Flevoland, Gelderland and Noord-Holland [WebENT]. Liander, the DSO in these areas, announced the inability to add any new connections in these regions [WebDN].Increasing grid infrastructure is an obvious yet logistically and financially challenging solution. According to Liander, investments on the scale of billions of euros are required to uphaul the entire grid while admitting that even such a huge financial investment may not be enough to resolve all the capacity problems [WebAL]. Only infrastructural additions are not nearly enough to resolve the grid issues of the energy transition. Rather than considering scenarios such as congestion or energy scarcity as exceptional and unexpected, it is important to forecast such scenarios and incorporate strategies to mitigate them into the initial energy planning itself.

The examples provided above show how consumers are affected by high energy prices and scarcity due to political instability on a global scale. Therefore, switching to renewable energy production by micro generators, such as rooftop PV and small-scale wind turbines leads to:

1. Reduction in the dependencies on energy supplies from unstable regions, and therefore leading to a higher security of supply. This added security then translates into trust and predictable prices for end-consumers.
2. Consumers becoming prosumers as they can produce their own electricity. As such, they become active stakeholders in the energy domain.
3. The electrification of energy-end use as renewable energy is often directly produced in the form of electricity. As a result, electricity will become a major source of energy for mobility and space heating, instead of fuel and natural gas. This effect is called the electrification.

However, not all is as nice as sketched above. Even though we become independent from other countries, we do become more dependent on the weather conditions that dictate how much energy will be available. Here with the note that weather conditions may become more extreme in the future due to climate change. Next to this, the electrification also puts a strain on the grid as mentioned. Even if we have the availability of energy due to favorable weather conditions on a national scale, we may not be able to transport it to all customers that request the energy due to grid congestion issues.

As a result, we face a highly dynamic energy supply system in which the dynamics may be even more challenging than those that resulted from the geo-political situation we faced in 2021 or the (mild) uptake of renewables in the last decade. It is possible to mitigate the effects of a highly and uncertain dynamic system through adaptation. That is, we need to be prepared for various scenarios by having measures in place that can flexibly adapt the use of the energy system to various (challenging) scenarios.

3.1 Goal of this deliverable

This deliverable investigates how communities can become adaptive and more resilient to the challenges ahead of us in the energy transition. Just like the global scale, also the local community scale needs to become less dependent on higher grid levels. This can be done by having more distributed assets, such as micro generators and battery storage systems.

We develop a model-based method to investigate the robustness and adaptivity of a community with respect to power and energy usage. This workflow allows to investigate different options and how it affects the degree of grid independence.

Next, we develop a theoretical foundation that describes different *energy modii*. An energy mode is a specific state of the local grid, which will subsequently affect energy usage and the control over flexible assets. This could be for example, congestion (i.e., limited distribution capacity) or scarcity of energy availability. For this we first formulate the different possible states and their definitions. It is envisioned that these modes can be discovered automatically through measurements or can be invoked (upfront) by external parties, such as the distribution service operator (e.g., in case of planned maintenance or forecasted problems).

From these modes, we derive how energy assets should be utilized, such that their flexibility is optimally used to satisfy the problems seen in the electricity grid, whilst also trying to keep the quality of service perceived by end-users as high as possible. The definitions of the different energy modii help in creating a transparent interface. This is not only a technical solution. The citizens also need to react, e.g., by postponing running the washing machine. We do so by translating the different modii in a clear and transparent way into e.g. messages on an app. These messages then tell the situation, if known for how long, and give practical tips on how users can help the system. The goal of this effort is to ensure that the (local) grid remains powered, and as many devices (especially must-run devices) can continue to operate.

This way, we ensure that local communities become resilient to the challenges we face in the energy transition. On the one hand, for developed countries, this concept of energy modii may become an essential part to allow for the integration of more renewables and ensure we meet our decarbonization targets in a cost-effective manner. On the other hand, for developing countries, these solutions may be used to tie (islanded) microgrids together with a weak grid and enable a higher quality of service by energy sharing. In this situation, the concept of energy modii may be utilized to avoid the need of rolling blackouts.

3.2 Research questions and objectives

Given the sketched context, the main objective is to come to a replicable modelling and analysis approach that can be utilized to investigate flexibility options to reach a more resilient and adaptive energy community. This method also integrates the use of optimization that utilizes different energy modii. Hence, the definition of these modii is also key.

We do so by investigating the following research questions:

1. How to model energy communities with flexible assets and subsequently evaluate different possible configurations with respect to autarky?
2. What possible internal and external circumstances have an effect on the energy system and its stability?
3. Can these different circumstances be translated into a limited set of abstract parameters that define the different energy modii?
4. How do these energy modii lead to different optimization objectives for energy management systems and the performance of a community with respect to autarky?
5. How can these modii be effectively, clearly and transparently communicated to end-users in order for them to assist the energy system?

3.3 Outline

The remainder of this deliverable is as follows. Chapter 3 presents related background information on the Dutch demonstrators and the context for the need of uniform energy modii. Furthermore, it provides a selection of relevant literature and modeling tools based on the work of SUSTENANCE’s Work Package 2 results so far. Chapter 4 presents a modelling methodology to assess the performance of energy communities and toolchain for design space exploration. Subsequently, Chapter 5 presents the theoretical framework for energy modii and the how both energy management systems and users can be incorporated in the generic definitions. Subsequently, evaluations of presented approaches on the different demonstrators are presented. Finally, Chapter 7 presents conclusions.

4 Background

This chapter presents relevant background to the challenge sketched for the energy system. First the current situation of the Dutch demonstration sites, which act as use-case, are presented. Next, relevant background on modelling and simulation of such energy communities is presented. The latter presents the important aspects that have already been elaborated on in SUSTENANCE deliverables D2.1 and D2.2.

4.1 Dutch Demonstrator Sites

Within the Netherlands, there are 2 main demonstration sites, namely the Vriendenerf demonstrator in Olst and the University of Twente Field Lab (smart parking place). Next, there are links with the Aardehuizen community, which forms a second residential community to validate the modelling concepts for reproducibility.

4.1.1 Vriendenerf demonstrator site

Vriendenerf is an energy community located in the municipality of Olst-Wijhe (Figure 4.1). The Vriendenerf community consists of 12 houses for elderly and one central common building where the community gathers. This common building also houses a guest room and shared appliances, such as a washing machine and tumble dryer. Additionally, there is a common shed to store bikes and the community has a shared (vegetable) garden. The interaction between the members of the community is high.

Figure 4.1: Location of Vriendenerf, the Dutch demonstration site

The 12 houses are built with a focus on sustainability in mind. The following sustainability measures have been taken:

1. The installed PV-panels produce 6400 kWh/year for a single corner house and 5600 kWh/year for a single in-between house on average.
2. Of this annual PV yield, it is estimated that annually 3500 kWh is used for heating, cooling, ventilation and domestic hot water production.
3. The houses are built according to the “Zero-on-the-Meter" (ZOM) or “Zero Energy Building” (ZEB) principle; each house produces as much energy as it consumes yearly. This energy balance is calculated for which an average thermostat setting of 20 °C is taken, as well as 150 litres of hot water is stored and consumed every 24 hours.

4. The houses in Vriendenerf are designed to minimize energy consumption for space heating. This has been achieved by three design decisions:
    a. High insulation factors
    b. Heat recovery ventilation system
    c. Heat pumps with a ground heat exchanger networks

The main demonstrator specifications are as follows:

- 12 houses divided into groups of 3 as shown in Figure 4.2.
- 69 PV-panels for each group of 3 houses.
- Each house is equipped with a heat pump, domestic hot water storage and ground source.
- Houses are fully insulated.
- Equipped with active air ventilation system.
- 5 EV charging stations.

Figure 4.2: 4 groups of 3 houses and 1 common house

Specific goals of Vriendenerf are as follows:

- Model heat-to-electricity systems and study their flexibility potential.
- Develop and demonstrate the integration of heat-to-electricity systems into a smart Energy Management Systems (EMS).
- Combine heat-to-electricity systems with batteries, electric vehicles and boilers to encourage a high-level of self-consumption within the energy community.

4.1.2 University of Twente Field Lab "SlimPark"

The University of Twente Field Lab, commonly named "SlimPark", which is an abbreviation for "Slim Parkeren" (Dutch for "Smart Parking"), is an electric vehicle charging station located at the University of Twente (Figure 4.3). It is the real-world laboratory of the Energy Management Research group of the University, in which Energy Management algorithms are tested in practice with real users. It is therefore an essential bridge from theory to practice. It allows students and researchers to test and validate new concepts close to their office when theory is proven in simulation studies, but not yet ready for practice.

An important aspect to this is testing the interaction between technology, algorithms and their end-users. The latter is hard to be modelled in simulation studies, if even possible. However, users form the most important aspect in the energy transition. If they do not embrace the technologies, then also the energy transition that depends on the technologies may be jeopardized.

The SlimPark Field Lab consists of the following components:

- 9 3-phase 22kW (32A per phase) Mennekes Amtron Pro AC chargers;
- 69 PV-panels of 360Wp each, making in total 25 kWp of rooftop solar panels;
- 25kW PV inverter;
- 30 kWh capacity with 20kW battery storage system;
- All components are connected to a 3-phase grid connection with a 125 A per phase capacityt.

Figure 4.3: The EV charging station at the UT campus [Picture Credit: Caroline Abbink].

All components are connected to an Energy Management System (EMS) for data gathering. Furthermore, the charging stations and battery can be controlled to allow for energy matching. The EMS in question is DEMKit, a software tool developed at the University of Twente. This software is developed with both simulation studies and demonstration in practice in mind. As such, it allows researchers to first study new control concepts in simulation. After verification, it can be deployed in practice with only minor modification due to the modular nature. More about DEMKit is presented in Section 4.2.

4.1.3 Aardehuizen Olst Demonstrator

The Aardehuizen ("Earth houses") are built after the earth ship concept to create sustainable houses. This community is used as a second community where the principles and methods, applied to the previous 2 presented demonstrators, can be tested for genericity and reproducibility. This neighbourhood consists of 24 households and again a community building. Many houses have PV panels installed and the houses are constructed in such a way that they optimally use the energy from the sun for space heating. The rest of the heating system differs significantly per house, with many wood stoves.

Most houses have a large buffer vessel for domestic hot water usage, which is connected to a heat collector. Lastly, the community has a solar carport with a similar setup as SlimPark, namely: controllable chargers, battery energy storage system, and PV (222 panels for approximately 70kWp).

4.2 Modelling tools

This section presents relevant background on modelling tools for smart grid control of neighbourhoods, based on the results from SUSTENANCE's Work Package 2. Based on these outcomes, we briefly present DEMKit and the Artificial Load Profile Generator (ALPG) tools [Hoog17]. Together they form a toolchain for modelling (Figure 4.4).

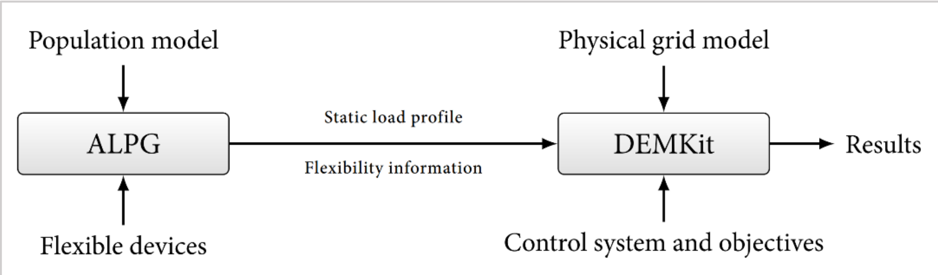


Figure 4.4: Toolchain of importing generated data into the optimization toolkit DEMKit [Hoog17]

4.2.1 DEMKit

DEMKit [Hoo17], short for Decentralized Energy Management toolkit, is an open source toolkit[1] designed for conducting simulations and real-world demonstration experiments involving smart grids and energy flexibility. It is designed as a cyber-physical systems approach and comprises of various algorithms that optimize the power profile and coordinate the same between various devices. DEMKit is a toolkit that can be used to model the energy grid with its various flexible entities and execute energy optimization and planning algorithms.

Within DEMKit, the energy grid can be modelled in a modular and hierarchical manner. Modular because DEMKit models each device with its own controller. For example, a *bufferDevice* (eg. Battery) would have its own *bufferController* agent (e.g., BatteryController). This makes the model scalable in terms of size but also allows for changes to the model by adding or removing components. This way, any structure of physical devices within a microgrid can be modelled. Furthermore, these abstract models are energy carrier agnostic. Hence multi-energy systems can be modelled as presented in [Homan19].

Next to the physical part, DEMKit also has modelling components for the digital system. For this it uses an *agent-based approach*. Hierarchical because devices and their respective agents communicate bidirectionally with higher-up controllers. For example, household devices and controllers communicate with a group controller at household level, which in turn, communicates with a group controller at neighbourhood level. Therefore, each controller acts as a child to a coordinator controller above it and as a coordinator controller to another child controller below it. Embedded within these control methods are also optimization algorithms, such as Profile Steering [Ger15] and double-sided auctions [Kok13].

[1] https://github.com/utwente-energy/demkit

The modular approach allows experts to test different algorithms and control strategies on the same physical model. Figure 4.5 shows such a model.

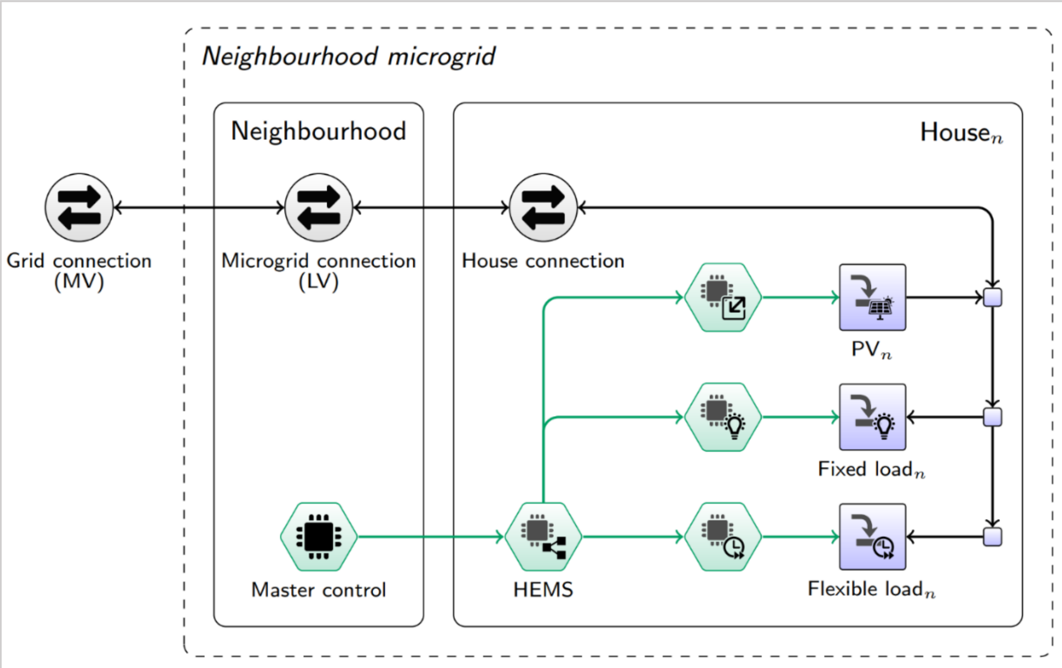
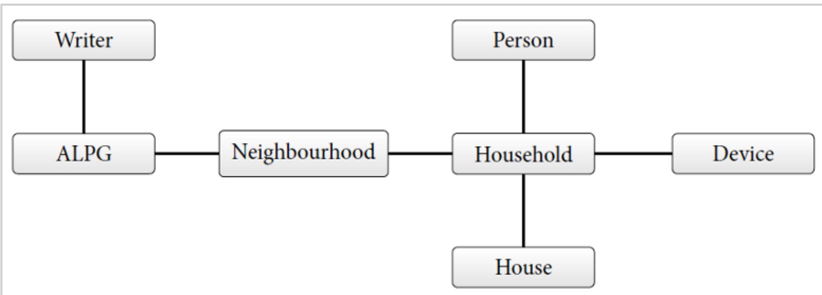


Figure 4.5: Generic DEMKit model for a household. Blue rectangles indicate physical device models, green hexagons indicate optimization algorithms and controllers controlling the devices [Homan19].

4.2.2 ALPG

Next to the DEMKit modelling tool, we use the open-source ALPG[2] (Artificial Load Profile Generator) tool [Hoo16] to generate input datasets of energy usage patterns in cases where real data is (still) missing. Furthermore, the ALPG explicitly specifies the energy flexibility, in the form of mathematical constraints, required for energy management systems to optimize the energy flows.

The input to ALPG is demographic information of the neighbourhood, physical location of the neighbourhood and historical weather data. The tool outputs realistic power profiles based on the expected activity of such a demographic. ALPG uses this high-level input data to generate both static power profiles as well as the power profiles for flexible devices such as electric vehicles and batteries. The ALPG ensures that the profiles generated are consistent with the stochastic behaviour patterns generated for the demographic. For example, the changes in domestic hot water changes in a house coincides with the house during which the house is occupied. Figure 4.6 shows the class diagram of ALPG.



[2] https://github.com/utwente-energy/alpg

Figure 4.6: Class diagram of the load generator [Hoog19].

These classes implement the following aspects required to generate realistic load profiles:

- **Persons:** This class decides the behaviour profile of a person by using a uncertainty variable to generate sleeping hours, waking hours, arrival times from work etc.
- **Devices:** This class stores information about the static load devices such as refrigerators and household lighting as well as information about the flexible devices such as EVs.
- **House:** This class location-specific information such as the recorded solar irradiation and also stores information such as the orientation of the roof to calculate the PV generation.
- **Households:** This class links the previous 3 classes; Person, Devices and House as well as annual power consumption values.
- **Writer:** This class is used to format the output of ALPG such that it is suitable to be used as input data by a simulation toolkit such as DEMKit.
- **ALPG:** This class is a coordinator class containing references to all the objects in the model and controls the profile generation process.

The resulting output of the ALPG is validated with a real-world dataset in [Hoo17]. Even though the tool only utilizes high level information about a neighbourhood, the overall power profile is very realistic (Figure 4.7). Furthermore, the ALPG is currently the only known tool that not only generates load profiles, but also provides flexibility information about specific devices, which is a crucial aspect for the evaluation of energy management strategies.

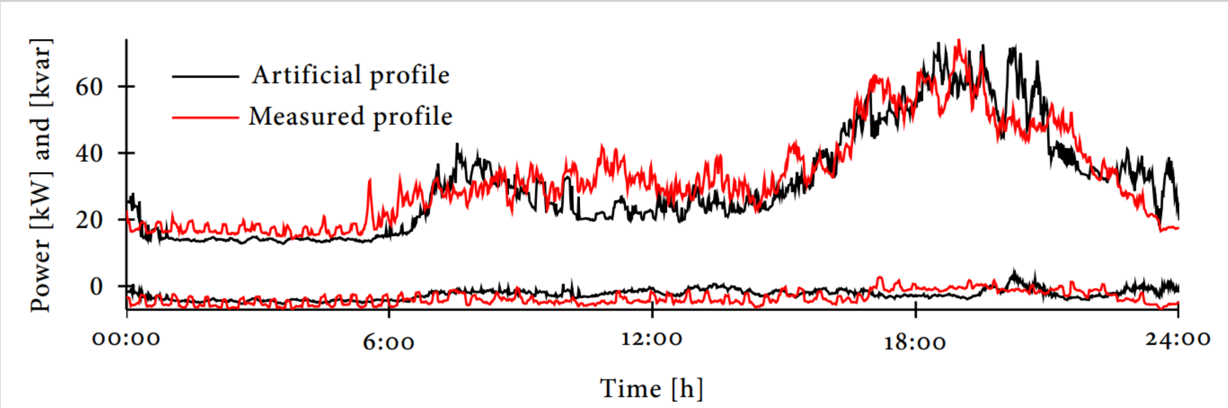


Figure 4.7: Output of the ALPG compared to real-world data [Hoo17].

4.3 Energy Management Algorithms

The device profiles generated by ALPG constitute the model of the EC. This EC model is used as input to DEMKit. DEMKit's modular nature permits the implementation of various DSM approaches on the EC model and the visualization of their improvements on the base model data. DSM approaches attempt to steer the aggregated EC profile towards a desired power profile. What is critical therefore is the specific steering signal sent to the HEMS. This steering signal is representative of the specific goal that the EC is attempting to achieve at the neighbourhood aggregated level. Steering signals can be of two types, namely, a price signal or a power signal.

In case of price signal steering, the neighbourhood controller sends information about day-ahead prices, attempting to incentivise individual HEMS to plan their consumption according to this price signal.

However, the consequence of price steering is that individual HEMS shift their consumption to intervals with the lowest price. This leads to the *peak-shifting* of the aggregated power peak and not the desired *peak-shaving* of the power peak. Also, sending customized price signals to each HEMS in order to avoid this behaviour runs into challenges of fairness in pricing.

In the case of power signal steering, the neighbourhood controller sends a desired power signal rather than a price signal to the HEMS. Gerards et al. argue that sending a signal that captures exactly what the neighbourhood controller desires is a better way to achieve peak-shaving [Ger19]. The algorithm for profile steering on the basis of power profiles is presented in Algorithm 1 and is explained below. Hereafter, the approach is referred to as profile steering (PS).

The neighbourhood controller creates a desired profile $\vec{p}$ that captures the goal of the EC. For example, the goal of grid independence can be captured in a desired profile $\vec{p}$ as a zero vector i.e. try to achieve energy balance. The current aggregate power profile of the EC is represented by the vector $\vec{x}$. Both $\vec{p}$ and $\vec{x}$ are vectors containing values for discrete time intervals into the future. PS is an iterative heuristic that attempts to minimize the Euclidean 2-norm distance between $\vec{p}$ and $\vec{x}$. At the start of a PS iteration, each child node m such as the individual HEMS receives the difference profile $\vec{d}$ (given as $\vec{d} = \vec{x} - \vec{p}$). Using this each child node calculates its local desired profile $\overrightarrow{p_m}$ (give as $\overrightarrow{p_m} = \overrightarrow{x_m} - \vec{d}$). Then each child node m creates a new profile optimized with respect to the just calculated local desired profile. Optimization here means minimizing $||\overrightarrow{\widehat{x_m}} - \overrightarrow{p_m}||_2$. Thereafter each child node (or each HEMS as in our case) calculates e_m and submits that to the coordinator one level above (e.g. neighbourhood group controller). The improvement that the child node can make on the main objective is represented by e_m.

The coordinator node chooses the child profile with the highest improvement e_m and sends this choice to its children. The child node m which is chosen updates their current local with candidate local (as $\overrightarrow{x_m} = \overrightarrow{\widehat{x_m}}$). The chosen child node calculates the delta profile $\vec{\delta} = \overrightarrow{\widehat{x_m}} - \overrightarrow{x_m}$ and updates the aggregate power profile $\vec{x}$. Successive PS iterations are carried out until no sufficient improvement can be achieved ($e_m < \varepsilon$) or a certain maximum number of iterations is completed.

Algorithm 1: Hierarchical PS algorithm

Request each child node $m \in \{1, ..., M\}$ to minimize $||\vec{x_m} - \vec{p_m}||_2$
$\vec{x} := \sum_{m=1}^{M} \vec{x_m}$
repeat
  $\vec{d} := \vec{x} - \vec{p}$ {Difference Vector}
  for $m \in \{1, ..., M\}$ **do**
    $\vec{p_m} = \vec{x_m} - \vec{d}$
    For child node m, find a planning $\vec{x_m}$ that minimizes $||\vec{\hat{x}_m} - \vec{p_m}||_2$
    $e_m = ||\vec{x_m} - \vec{p_m}||_2 - ||\vec{\hat{x}_m} - \vec{p_m}||_2$ {Improvement of profile of child node m}
  end for
  Find node m with highest improvement e_m
  $\vec{x} := \vec{x} + \vec{\delta}(\vec{\delta} = \vec{\hat{x}_m} - \vec{x_m})$ {Update the aggregate power profile using the delta profile}
  $\vec{x_m} = \vec{\hat{x}_m}$ {Update the profile of node m}
until $e_m < \epsilon$ {Repeat while sufficient improvement}

4.4 Grid Management

For over a decade, the Netherlands has not executed the necessary grid reinforcements for the imminent energy transition [WebNos]. Consequently, the Netherlands is facing a serious issue in their efforts to decarbonize the energy use through installation of RES and the electrification. This problem first became apparent on the transmission grid and medium voltage parts of the distribution grid. In some areas no capacity is provided to install new solar fields due to grid congestion. But also, more and more potential energy customers (e.g., companies) cannot be connected. The current status of the grid congestion can be seen on the *capaciteitskaart* [WebNetb].

But it is not only the higher voltage levels that suffer, also the low voltage level to which residential customers are connected, start to show problems. This was first shown in an experiment in 2015 [Hoog17Loch] where massive EV charging led to a service interruption in a neighbourhood. Nowadays, Dutch DSO Alliander acknowledges the problems and warns for more interruptions as the energy transition continues [WebAlnder]. Upgrading all neighbourhood grids is practically impossible as it consists of 220k km underground cable, making up for two-thirds of the complete Dutch electricity infrastructure. Currently, the first low voltage customers are already denied a larger connection.

These capacity issues are based on worst-case situations that can theoretically occur. However, in practice this is very unlikely, yet the DSOs need to be sure that no problems arise. Therefore, various solutions are presented or are under development that can unlock unused capacity whilst providing the DSO with the security that no overloading will occur. A promising concept is the Universal Smart Energy Framework (USEF). Here a traffic-light concept is presented with different levels of control to avoid blackouts (Figure 4.8).

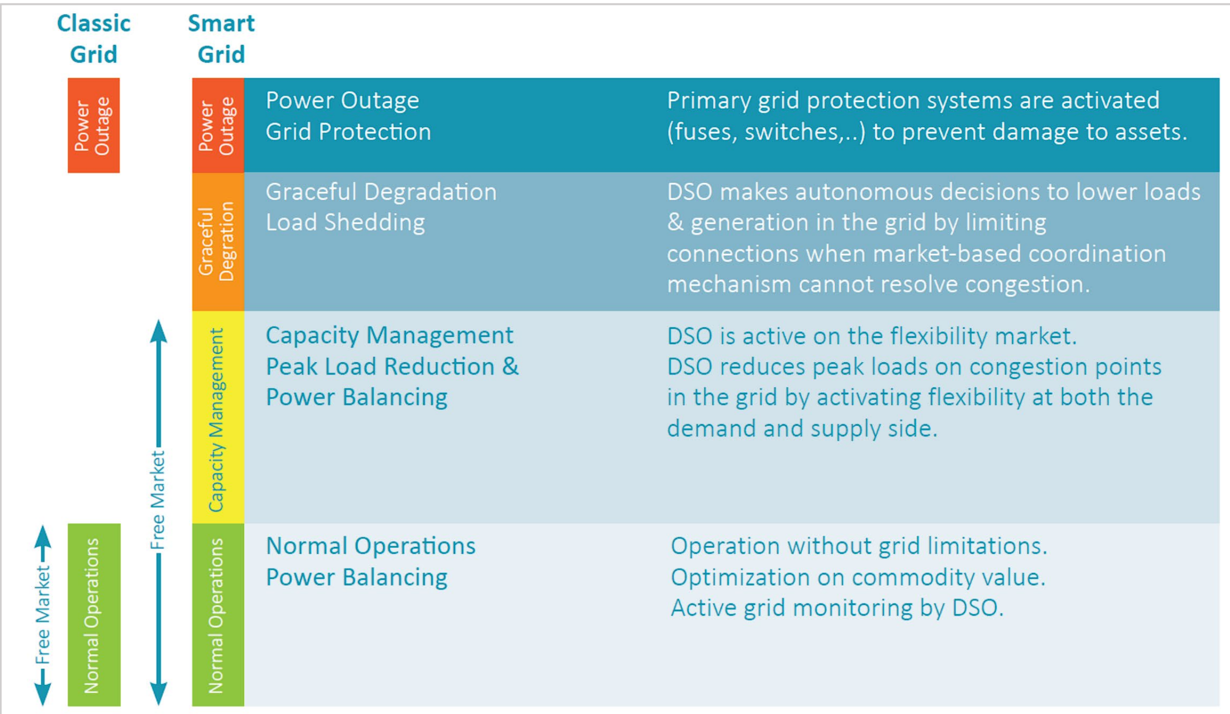


Figure 4.8: USEF traffic light concept [WebUSEF]

One solution in place for companies is the GOPACS platform. In this platform, grid congestion is resolved by the DSO through better matching of generation and consumption in the grid. To achieve this, the DSO compensates for the price difference of purchasing energy from a local, but more expensive, producer. Furthermore, Dutch DSO's are looking in different contract forms, such as Non-Firm Capacity contracts, in which the offered capacity is time dependent. For residential customers, more fundamental research is ongoing for local energy markets within the MegaMind project [WebMMind]. These are solutions for the yellow phase in the USEF framework.

So far, the orange phase, in which the DSO gains direct control, has been mostly neglected. However, recent developments make it apparent that solutions need to be in place. One project is the GridShield project [WebGridSh] in which charging stations are autonomously throttled upon measured congestion issues at the medium to low voltage transformer. The aim of this project is to standardize means of control for DSOs to avoid outages due to charging. In Germany solutions are also being developed to be able to control any device that can draw over 3.7kW from the grid [WebInga]. This is a development that leverages the possibilities provided by based on § 14a of the *Energiewirtschaftsgesetz* (German energy law) [EIAAct22].

These developments are complimentary to the energy modii concept that will be presented in Chapter 5 of this deliverable. However, here the goal is not only to seek solutions in the technical integration domain, but also to incorporate the end-users in this process.

5 Autarkic Neighbourhood Modelling

This chapter focusses on the first research question by presenting a method to model and evaluate the energy performance of a multi-energy neighbourhood. For this a 5-step method and toolchain utilizing DEMKit and ALPG are presented. Next, we evaluate the method presented using the Vriendenerf demonstrator use-case. The 5-step methodology is illustrated in Figure 5.1.

5.1 Methodology

In this section we describe the 5-step methodology followed starting with information from the test site and eventually realizing a DEMKit model with energy modii incorporated in it. The concept of energy modii is elaborated on in detail in Chapter 5.

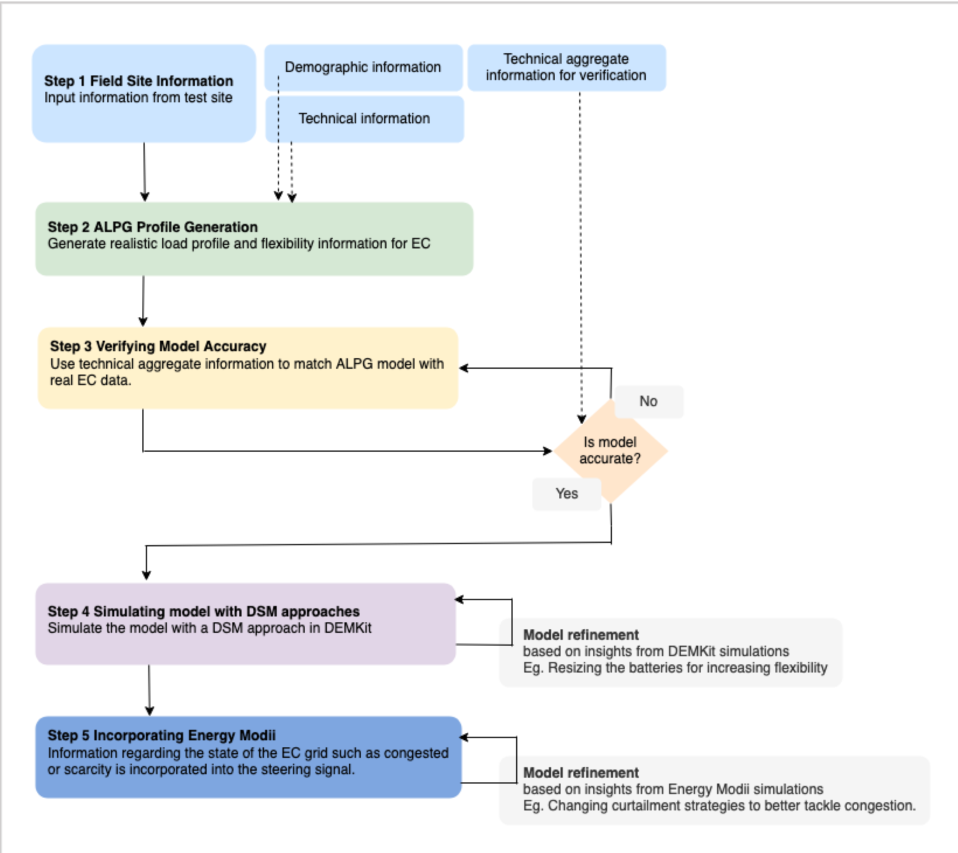


Figure 5.1: 5-step methodology to evaluate performance of multi-energy neighbourhood.

Step 1 Field Site Information

The first step in model building is to acquire information from the test site. This information consists of two parts. The first part is the demographic information. This part of the information relates to the social composition of each house and the working status of the adult members of the household in the energy community (EC). The second part of the information is the technical part. This part consists of knowing what the penetration of distributed energy resources (DERs) such as PV panels, electric vehicles, heat pumps is in the EC. Additionally, aggregate technical information such as the total energy demand and the total energy production from DERs is recorded. This aggregate information is used further on in step 3 for model verification.

Step 2 ALPG Profile Generation

The social part and the technical part of the information acquired in step 1 is used as input to ALPG. ALPG uses demographic statistics from social statistics collection databases such as CBS [WebCBS] and combines it with the technical part of the information from step 1 to generate both realistic load profile and flexibility information for the smart devices in the neighbourhood. ALPG also ensures that the allotment of smart devices such as electric vehicles or heat pumps is in accordance with the device penetration information recorded in step 1. The output of Step 2 is a collection of realistic load profiles for the EC, referred to here onwards as a model. From this a DEMKit scenario is generated and simulated.

Step 3 Verifying model accuracy

In Step 3, the simulation output model from step 2 is verified. This verification is done by comparing and checking the similarity in the total energy demand and production generated by ALPG and the aggregate technical information recorded from the field site in step 1. A sufficient match between the model data and the field data implies a model that is accurate and can be used for testing DSM approaches in step 4. A mismatch between the aggregate information from the field and data from the model requires corrections in the input to ALPG or manual adoption of the DEMKit model. Therefore step 2 and step 3 form an iterative loop. The output of step 3 is a model of the EC that has been confirmed to be representative of the actual EC.

Step 4 Simulating model with DSM approaches

In this step, a DSM approach can be incorporated into the EC model to investigate the effect of that DSM approach on peak-shaving or reducing CO2 emissions, to name a few objectives. The DSM approach implemented would make use of the flexibility information generated by ALPG to achieve its objective. Such a simulation of a DSM approach applied on realistic EC model data can be executed in an energy management software toolkit such as DEMKit. DEMkit simulations may be done in various time intervals as required and various simulation parameters such as the use of congestion points or the implementation of forced curtailment can be activated if desired to investigate their effect on the EC.

For this step, with the base model in place, we envision an iterative process in which DEMKit is used as a decision support tool. This means that an expert judges the output provided by DEMKit and manually makes adjustments to the model that fit the physical constraints, economic feasibility and the preference of the members of an energy community. Therefore, multiple DEMKit simulations with different parameters such as additional storage, PV etc. may be conducted on the same EC model from ALPG.

We note that this process may also be aided by optimization techniques, such as metaheuristic or genetic algorithms. However, due to the vast complexity of the technical search space and the human factor in the design process, we do not believe that this results in a better and socially acceptable design. The efficiency of the optimization algorithms embedded in DEMKit also makes it possible to perform quick simulations.

Step 5 Incorporating Energy Modii

In this step, the information about the state of the EC grid in each time interval is incorporated into the signal or power profile of the EC grid. The EC grid can be in various modes post the initial DSM planning such as a congestion mode or a scarcity mode, for example. The former implies that the DSM planning has intervals wherein the physical constraints of the transformer cable is being exceeded. The latter implies that the energy required by the community as the planning is not available creating a situation of energy scarcity. Knowing which grid mode the EC arrives in as part of the day-ahead planning can aid in activating the appropriate modii mitigation strategy and enhance the EC grid's ability to recognize and deal with undesirable situations. Implementing the modii mitigation strategy and investigating its effects also form an internal loop in step 5. The various energy modii are described in detail in Chapter 5.

The results from the DEMKit-energymodii simulations aid in making decisions such as investigating optimal battery sizing for achieving various degrees of grid independence in the EC. Here it is important to note that financial component costs are not considered in these simulations. The reason for this is two-fold in nature. Firstly, the objective of these simulations and the deliverable in general, is to put forward a concrete methodology that can be universally applied to any EC and is agnostic to the demographic or the technical parameters of that EC. Secondly, this makes the methodology time agnostic such that the inferences derived from the same are not dependent on the constantly fluctuating costs of components.

5.2 Vriendenerf DEMKit Model

We use the Vriendenerf demonstrator to evaluate the effectiveness of the presented 5-step method. For the two other demonstrators as presented in Chapter 3 a similar strategy was employed. However, for these locations we present the main findings and evaluations in Chapter 6.

5.2.1 Vriendenerf base model parameters

The DEMKit model for Vriendenerf is using data generated from ALPG and simulated using DEMKit. For data generation using ALPG, a community consisting of 12 *dualRetired* houses is considered. Additionally, the 13th dwelling, the middenhuis or common house, is considered as a *singleRetired* house. We consider a 100% penetration of PV, heatpumps and induction cooking. The PV is setup to match the specifications provided. 5 dwellings are assigned an EV and none of the dwellings have a battery. These specifications mirror the on-field conditions. 1 year of data is simulated in DEMKit in intervals of 15 minutes.

5.2.2 Vriendenerf base model verification

Firstly, we simulate the Vriendenerf scenario with no DSM activated (noCtrl). The 13 dwellings are numbered as House 0 to House 12. Figure 5.2 shows the net energy consumption (kWh) from the smart meter of House 0 for a 1 year simulation done in 15 minutes intervals and Figure 5.3 shows the same for House 7. Table 5.1 lists the total annual consumption of all 13 dwellings. Negative values mean productions (PV panels) and positive values mean consumption.

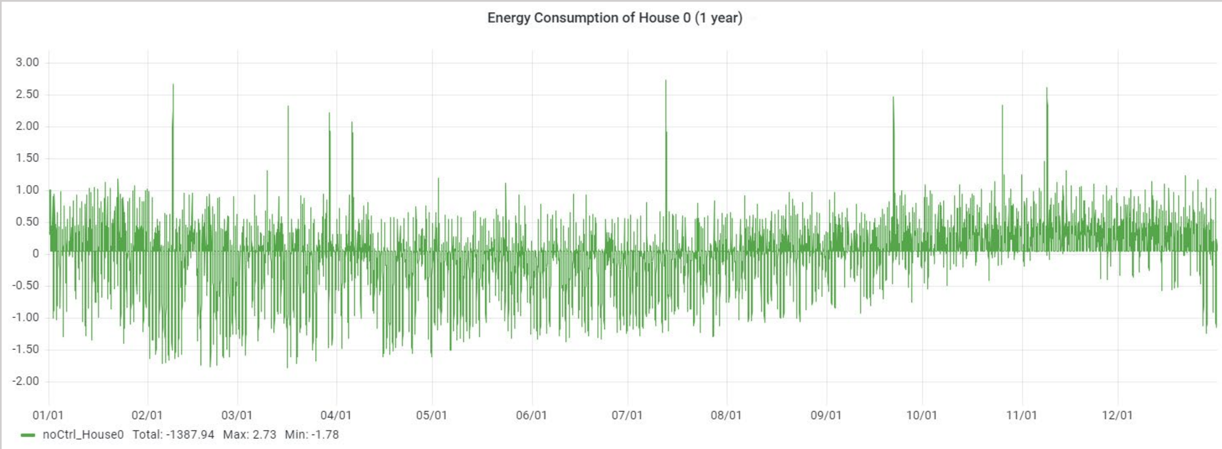


Figure 5.2: Annual consumption of House 0 from the Vriendenerf DEMKit model

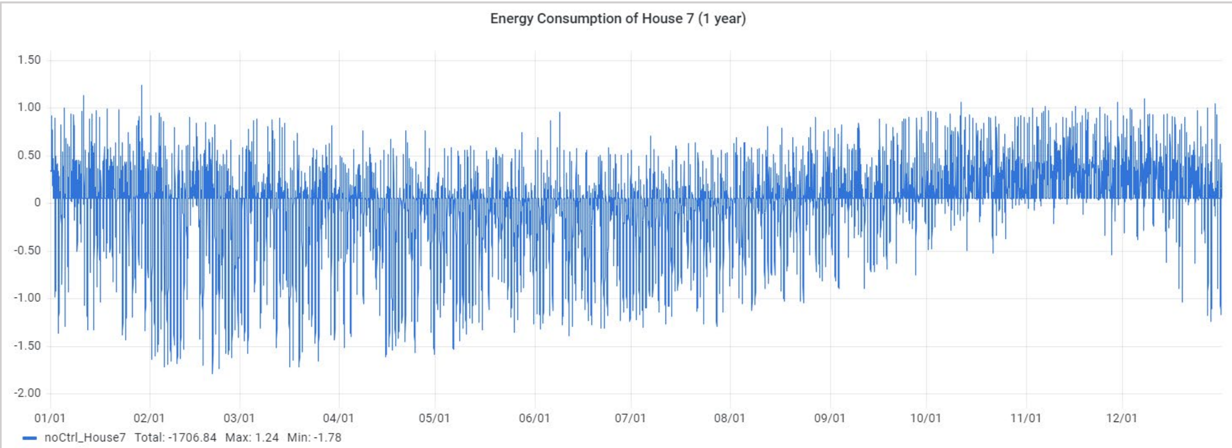


Figure 5.3: Annual consumption of House 7 from the Vriendenerf DEMKit model

Table 5.1: Total annual consumption values of all 13 dwellings from the DEMKit model.

House No.	Total annual energy consumption (kWh/y)	**House No.**	Total annual energy consumption (kWh/y)
0	-1387.94	7	-1706.84
1	-1883.32	8	-2343.91
2	-1260.00	9	-1566.39
3	-1869.03	10	-1889.27
4	-1637.02	11	-1701.76
5	-1547.82	12	996.51
6	-1589.01		

Table 5.1 shows that each house, other than House 12, produces a surplus of energy annually. This illustrates that the total annual production from the PV panels is more than the total annual

consumption and that the houses can completely cover their energy consumption with PV production, albeit, on a net annual basis. This aspect of surplus production coincides accurately with the actual reported average energy statistics from Vriendenerf. Table 5.2 shows the PV panel yield and the annual energy consumption by the houses for heating, cooling, ventilation, and hot water. Table 5.2 shows that the houses in Vriendenerf are designed with a "zero-on-the-meter" principle. However, on-field information indicates that the houses actually have a huge surplus of production at the end of the year. This aspect is successfully captured in our model.

Table 5.2: Average energy statistics for a house in Vriendenerf [WebVriend]

	Corner house (in group of 3) (kWh/y)	Middle house (in group of 3) (kWh/y)
PV Panels yield	6400	5600
Warming, cooling, ventilation and warmwater	3500	3000
Energy available for other household use	2900	2600

5.2.3 Vriendenerf DEMKit scenarios for autarky investigation

Having established the validity of the Vriendenerf DEMKit model, in this section, we attempt to study the community's potential for autarky in time. Our objective in the following simulations is to investigate the community's ability to offset their energy consumption with their production in each time interval. No demand side management is applied in the base simulation and each dwelling is assigned a 5 kWh (1C rate) battery (noCtrl_5). In the second simulation, we use the profile steering algorithm [Ger15] for DSM with the same battery parameters as in the base simulation (withCtrl_5). Figure 5.4 shows the energy consumption of the entire EC for the entire year and Figure 5.5 the same only for the winter months of January and February without any control (noCtrl_5) and with profile steering control (withCtrl_5). The energy consumption profile with and without profile steering is shown only for the months of Jan and Feb simply to illustrate the aspect peak-shaving clearly.

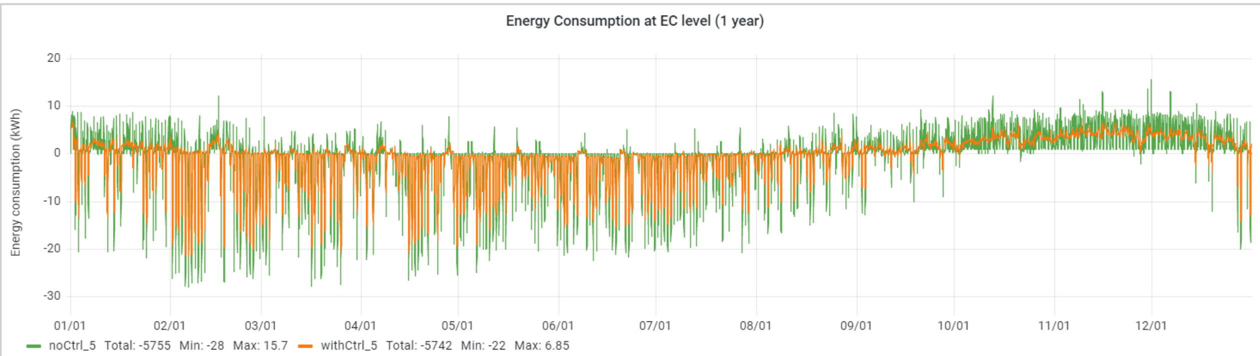


Figure 5.4: Energy consumption at EC level with and without profile steering control for 1 year

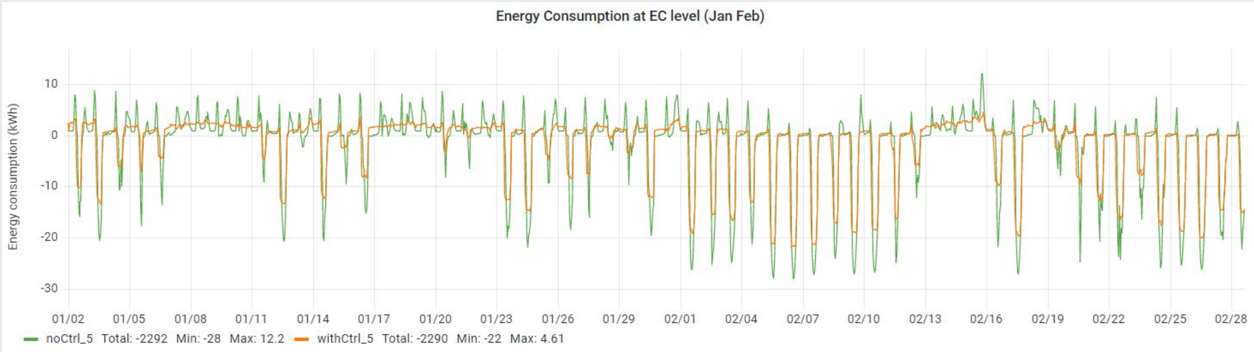


Figure 5.5: Energy consumption at EC level with and without profile steering control (Jan and Feb only)

Next, we simulate scenarios wherein each dwelling is allotted a battery with increased capacity and charging power. The aim here is to investigate how battery sizing influences the neighbourhood's autarky potential. Figure 5.6 shows the aggregate power profile for the first 14 days in the month of January for all the 14 scenarios.

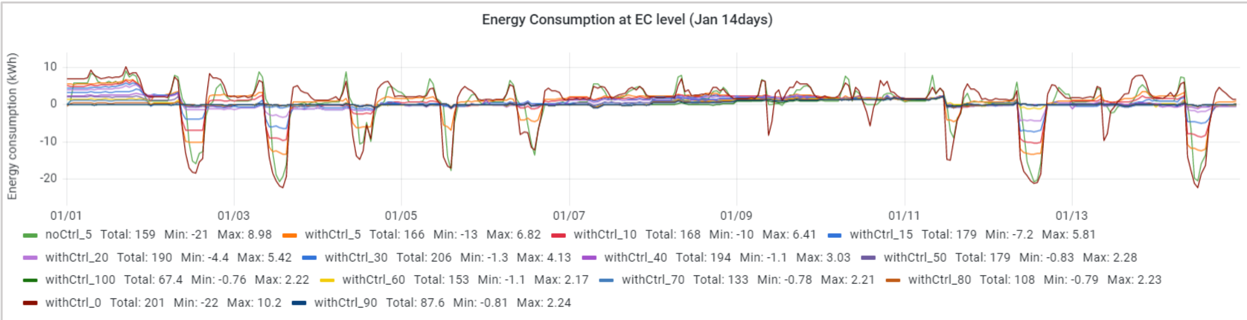


Figure 5.6: Increased peak-shaving effect due to increase in battery capacity.

5.2.4 Autarky achieved vs EC Flexibility

In this section we illustrate the relationship between autarky achieved by the EC with respect to the flexibility added to the EC. In our case, the additional battery capacity represents the flexibility addition. Figure 5.7 illustrates this relationship as an exponential decay function. As the battery capacity per house increases (rightwards along the positive x-axis), the amount of energy annually imported from the grid decreases (downwards along the negative y-axis).

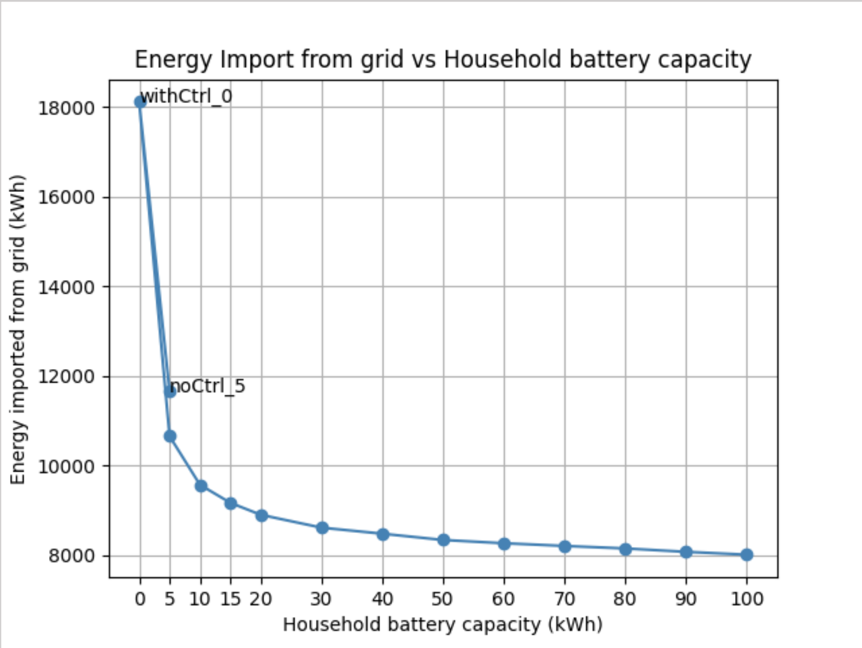


Figure 5.7: Decaying exponent relationship between energy import and EC flexibility.

This shows that as more flexibility in terms of storage is added to the EC, the *autarkic value* or *autarkic payback* of that flexibility decreases. This discourages investments in ever-increasing battery sizes and placing further emphasis on the concept energy modii. Rather than expanding battery capacities to limits that are both extreme in terms of physical space requirements as well as in terms of the financial cost of such huge investments in storage, the concept of energy modii may offer a smart way to deal with scenarios such as excess energy demand from the EC. The concept of energy modii offers a sensible methodology to deal with various EC scenarios to achieve autarky and are defined in detail in the next chapter.

6 Energy Modii

6.1 *Grid Structure*

The electric grid in an energy community can be divided into the physical layer and the ICT layer. The physical layer consists of the actual flow of energy and the power electronics components (e.g. transformers). Given that the use cases consist of prosumer entities, bi-directional flow of energy is considered in the physical layer.

The prosumer entities when considered as nodes in a communication network, comprise the ICT layer of the grid. The ICT layer consists of a decentralized control hierarchy as visualized in Figure 6.1. Each device has its own controller. A device controller acts as the control-agent on behalf of its device. It can read parameters of the device and steer the power profile of that device in accordance with some external stimuli. Thus, the device and its own controller form a stand-alone module. Such modular design permits scalability and the ability to easily implement new changes in a rapidly evolving energy ecosystem. The device controllers communicate with the group controller above it in the decentralized hierarchy i.e the house controller. The hardware and software of such a house controller can be part of the HEMS. The house controllers communicate in turn communicate with the fleet controller above them in hierarchy, which is the neighbourhood controller. The neighbourhood controller sends a steering signal to the house controllers. The house controller further passes down this steering signal to its child nodes i.e., the device controllers. The neighbourhood controller can monitor the power flow at the transformer level via sensor values and can send control signals in return as well. Similarly, the house controller can sense the power values for the house and determine appropriate control signals.

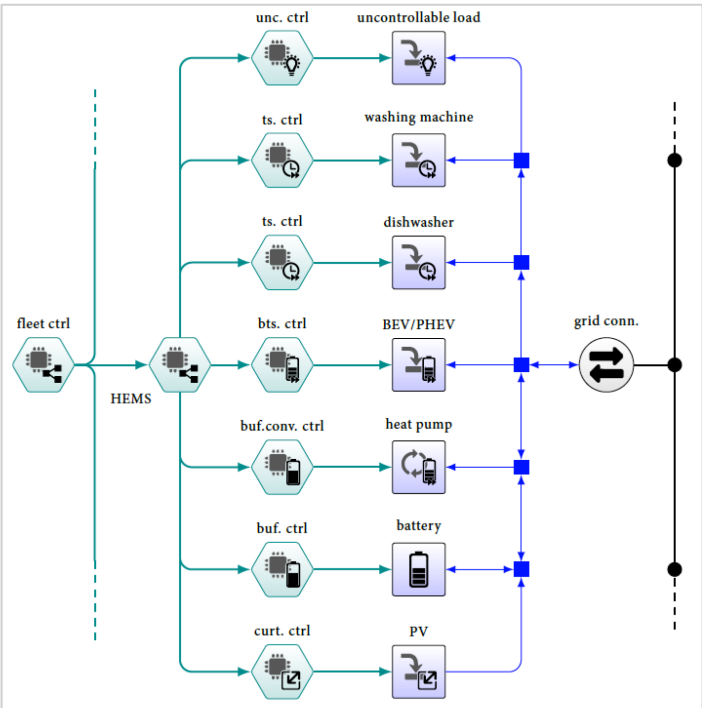


Figure 6.1: Decentralized control hierarchy consisting of devices and their controllers and the fleet controller [Hoog19].

This decentralized control hierarchy must be used to protect the EC grid and recover from undesirable scenarios or modes. Therefore, the information about grid modii must be embedded into the steering signals sent from higher-level fleet controllers to child controllers for them to incorporate them into their planning. In the next section, we define the 4 modes of the physical EC grid and the energy and power conditions that can trigger each.

6.2 *The 4 modii in the physical grid layer*

6.2.1 Power variables

$\vec{p}$ is the day-ahead aggregate power profile of the neighbourhood. If we assume N total intervals in 1 day ahead planning, then $\vec{p}$ can be defined as a vector of N samples, going from 0 to N-1.

$$\vec{p} = [p_0, p_1, \dots, p_{N-1}]$$

A positive power value represents power production, and a negative power value represents power consumption.

6.2.2 Energy variables

$\vec{j}$ is the day-ahead aggregate energy profile of the neighbourhood. The energy profile is defined as a vector of N samples, each sample representing the energy consumed or produced in that interval. A positive value represents energy consumption, and a negative value represents energy production.

$$\vec{j} = [j_0, j_1, \dots, j_{N-1}]$$

Furthermore, we distinguish between the aggregate energy profile of the neighbourhood and the energy profile (availability) from the main grid or the external grid.

$\vec{j}_{grid}$ is the energy supply from the main grid for N intervals.

$\vec{j}_{ec}$ is the energy demand of the EC for N intervals.

6.2.3 Time variables

The day-ahead planning is done for N time intervals. It consists of N-1 samples. A contiguous set of time intervals defines a time period. An energy mode is defined as a state the grid is in during a certain time period. Thus, an energy mode can apply for 1 or more contiguous intervals of time. This is visualized in Figure 6.2. It is important to note that the energy mode time period $\{0,1, \dots M-1\}$ is always part of the the day-ahead time period $\{0,1, \dots N-1\}$.

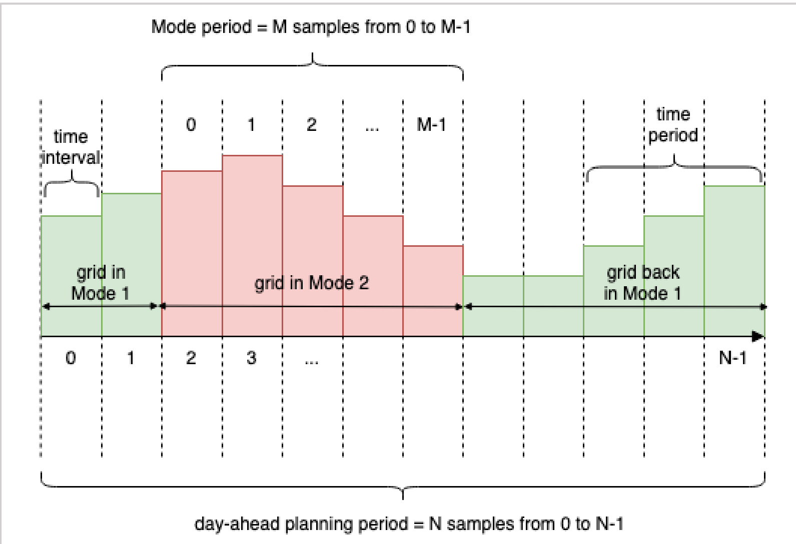


Figure 6.2: A Day-ahead planning of N intervals consists of 1 or more energy modii. Each modii stretches over 1 or more time intervals (M intervals).

6.2.4 4 energy modes of the physical EC grid

A mode is defined as a state in which the grid is in during a certain time period. A grid may arrive in one of the four modes explained below based on the aggregate energy demand or power values of the grid.

1. **Connected Mode:** This is the desired mode which the energy community should ideally be in at all time intervals. This is represented as a power condition i.e. the power flowing through the transformer is within its limit and an energy condition i.e. the energy demand of the community can be met with its own distributed energy resources and/or the energy supply from the external grid.

Definition: The physical grid is said to be in Connected Mode during period $m \in \{0, 1, M-1\}$ *if:*
in the power domain:

$$p_m < \vec{p}_{upper} \; where \; \vec{p}_m \in \vec{p} \; for \; m \in \{0, 1, \dots M-1\}$$
$$p_m > \vec{p}_{lower} \; where \; \vec{p}_m \in \vec{p} \; for \; m \in \{0, 1, \dots M-1\}$$

and in the energy domain:

$$\vec{J}_{ec_m} < \vec{J}_{grid_m} \; where \; \vec{J}_{ec_m} \in \vec{J}_{ec} \; and \; \vec{J}_{grid_m} \in \vec{J}_{grid} \; for \; all \; m \in [0, 1, \dots M-1]$$

Deviations from the power domain and energy domain criteria can be used to derive the following 3 undesirable modes of the energy community grid.

2. **Congestion Mode:** A community is said to be in this mode when the power level in a certain time period is higher than the power rating of the neighbourhood transformer.

Definition: The physical grid is said to be in Congestion Mode during period $m \in \{0, 1, M-1\}$ *if*
in the power domain:

$$\vec{p}_m > \vec{p}_{upper} \; where \; \vec{p}_m \in \vec{p} \; for \; m \in \{0, 1, \dots M-1\} \; \textit{(excess power production)}$$

or

$$\vec{p}_m < \vec{p}_{lower} \; where \; \vec{p}_m \in \vec{p} \; for \; m \in \{0, 1, \dots M-1\} \; \textit{(excess power consumption)}$$

3. **Scarcity Mode:** A community is said to be in a scarcity mode during a certain time period when the energy demand of the community exceeds the supply in those time intervals.

Definition: The physical grid is said to be in Scarcity Mode during period $m \in \{0, 1, M-1\}$ *if*
in the energy domain:

$$\vec{J}_{ec_m} > \vec{J}_{grid_m} \; where \; \vec{J}_{ec_m} \in \vec{J}_{ec} \; and \; \vec{J}_{grid_m} \in \vec{J}_{grid} \; for \; m \in \{0, 1, \dots M-1\}$$

(excess energy demand)

4. **Disconnected Mode:** A community is said to be in a disconnected mode when the physical connection with the external grid breaks.

Definition: The physical grid is said to be in Disconnected Mode during period $m \in \{0, 1, M-1\}$ *if*
in the power domain:

$$\vec{p}_{upper} = \vec{p}_{lower} = \vec{p}_m = 0 \; where \; \vec{p}_m \in \vec{p} \; for \; m \in \{0, 1, \dots M-1\} \; \textit{(zero power flow)}$$

The 4 physical grid energy modes and their theoretical definitions are summarized in Table 6.1.

Table 6.1: Summary of 4 physical EC grid energy modes and their theoretical descriptions.

Grid mode	Nature	Domain	Explanation	Theoretical description
Connected	Desired	Power	Power via transformer is within limits.	$\vec{p}_k < \vec{p}_{upper}$ $\vec{p}_k > \vec{p}_{lower}$
		Energy	Energy consumption of EC is fulfilled.	${\vec{J}_{ec}}_k < {\vec{J}_{grid}}_k$
Congested	Undesired	Power	Power via transformer is exceeding cable power limit.	$\vec{p}_k > \vec{p}_{upper}$ and / or $\vec{p}_k < \vec{p}_{lower}$
Scarcity	Undesired	Energy	Energy consumption of EC cannot be fulfilled by external main grid.	${\vec{J}_{ec}}_k > {\vec{J}_{grid}}_k$
Disconnected	Undesired	Energy	Connection with the external grid is broken. This mode can be a result of the Congested Mode.	$\vec{p}_{upper} = \vec{p}_{lower} = 0$ $\vec{p}_k = 0$

6.3 *Modii Mitigation strategies*

In the preceding section, the concept of energy modii for ECs was explained. In this Chapter we put forward possible strategies to deal with the energy modii by leveraging the EC's flexibility. The mitigation strategies explained below are illustrated in the flowchart of Figure 6.3.

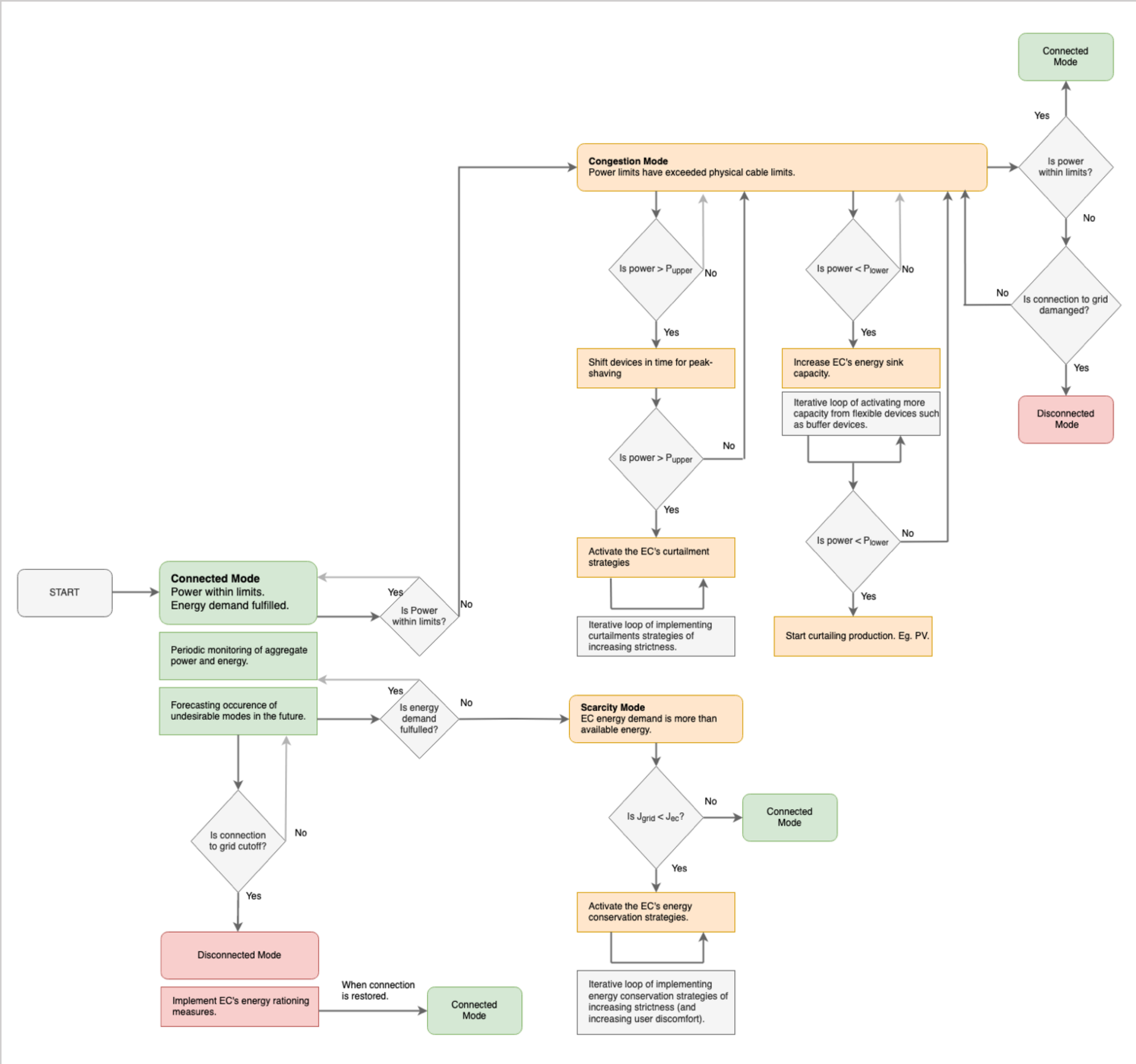


Figure 6.3: Flowchart of the 4 energy modii and the mitigation strategies for undesirable modii.

6.3.1 Connected Mode

The connected mode is the desired energy mode of the EC. However, in the connected mode, periodic forecasting can predict the onset of an undesired mode. The connected mode can thus act as a *preparation mode* for all the remaining 3 undesired modii. In the connected mode, 'business-as-usual' profile steering planning is done and executed. However, the connected mode can also be used to come up with backup 'in-case-of' plannings as well. These can be alternate power planning to implement in case of a congestion in the grid or in the case of energy scarcity. It may be that there are certain intervals during the day when there is a high change of congestion or scarcity occurring. Back-up plannings can be created to be activated quickly in the case of such undesired modii triggering at predictable intervals in the day.

6.3.2 Congestion Mode

When the neighbourhood profile indicates a congestion interval (or intervals), it is important to first understand the nature of the congestion. A congestion interval may be caused due to excess production from the community, for example the PV production power exceeding (becoming more negative than)

$\vec{p}_{lower}$. In this case, the community's potential as an *energy sink* must be increased. This can be done my charging the batteries to a higher end state of charge or increasing the end state of charge of electric vehicle, both of which are forms of a bufferDevice.

A congestion mode can be triggered due to excess demand from the community as well. Here the power demand exceeds the limit $\vec{p}_{upper}$. In this case, first a DSM algorithm such as profile steering can be used to shift flexible devices in time such that the power peak can be brought below the $\vec{p}_{upper}$ limit. If the first step doesn't achieve the desired decrease in power, then demand curtailment strategies can be implemented. Demand curtailment strategies can take the form of reducing the end state of charge for EVs. They can also place full control in the hands of the community inhabitants by letting inhabitants by letting them place This illustrates that the modii mitigation strategies developed strive to achieve the desired mitigation at minimal (ideally zero) user discomfort.

6.3.3 Scarcity Mode

When this mode is triggered, it implies that the amount of energy required by the community over the scarcity intervals is more than the available amount of energy from the external grid. Here we assume that the energy demand of the community already includes some demand that is offset by the DER production from the community itself. Therefore, the total energy demand of the community over the scarcity intervals $\vec{J}_{ec_k}$ must be brought below the available 'bucket' of energy from the external grid $\vec{J}_{grid_k}$. This requires demand curtailment strategies to be activated such that the energy demand of the EC is reduced, and the available energy is conserved. These demand curtailment strategies are similar to the ones used to alleviate an excess demand induced congestion. Flexibility of various devices can be used to bring the net community demand under the available energy bucket. Optimization algorithms can simulate various demand reduction options, the mitigation potential of each option and the decrease in user comfort for each option. Which demand reduction option to choose then can be a user choice.

6.3.4 Disconnected Mode

When the EC grid is in disconnected mode, it means the physical connected with the external main grid is cut-off. The EC grid is physically islanded, but not by choice of course. A disconnected mode can be the result of the mitigation strategies in the congestion mode not achieving the desired success. In the disconnected interval k, no energy import from the external grid is possible ($\vec{J}_{grid_k} = 0$). In this case demand curtailment strategies need to be implemented. These demand curtailment strategies could be of a more extreme nature in the disconnected mode. For example, ECs can classify device types into critical, moderate and least important categories. Critical device types can be allotted energy in the planning while the moderate and least important device types get very less or zero allotment of energy. Essentially the EC determines energy rationing measures which the HEMS of all houses communicate with each other to collectively implement. This emphasizes the need for clear target-specific user feedback as explained later in Section 5.3.5. Energy rationing in the disconnected mode underscores the importance of investing in energy storage in the EC and researching the optimal sizing of the same. For example, batteries can have a certain non-usable lower threshold of energy. This *emergency energy* can only be used for energy rationing in the disconnected mode.

6.3.5 User Communication and User Interfaces

User interaction plays a critical role in the effectiveness of DSM approaches and the concept of energy modii. User interaction may even be more impactful in reducing energy consumption, especially during congestion energy mode or scarcity energy mode, than simply improving the technological efficiency of appliances [Herring06]. Herring argues that improving the technical consumption efficiency reduces the price of energy making it more affordable. This increased affordability only increases the end-user's ability to use more energy resulting a 'rebound' effect. Herring argues in favour of active energy conservation as a means of energy use curtailment during intervals of undesirable energy modii.

When we talk about user interaction, two questions arise. Firstly, what should the 'interaction' exactly look like and secondly, who exactly is the 'user' with whom this interaction should be done. What should be shown and to whom should it be shown, to achieve effective implementation of the energy conservation behaviour by the energy modii. The research into feedback intervention theory (FIT) by McCalley et al. throws light on the first question. McCalley et al. argue that user interaction must be guided by FIT-type messages rather than generic goals [McCalley11]. FIT states that any intervention that results in achieving an objective at a hierarchical level other than the level at which the conservation action needs to be performed, will only hinder the conservation action itself and compromise user performance. The authors postulate that the energy-conservation feedback given to the user must be at the same level at which the energy conservation task is intended to be executed. This increases the chances of the energy conservation task being executed by the user. Furthermore, De Vries et al. discuss the difference between acting habits and non-acting habits and how each relates to the enactment of energy conservation intentions [Vries11]. Their research underscores the strong mental link between the situation and goal-oriented behaviour when said behaviour is activated repeatedly in the same situation. The repeated activation transforms the behaviour into an acting habit or a non-acting habit. De Vries et al. show that, once an acting or non-acting habit if formed, such habits become automatically triggered in the situation that generated them, making it tougher to alter either. Now we come to the second question about 'whom' the FIT-type messages must be shown. According to Geelen at al. home energy management systems (HEMS) must connect individual users with the community as well as the other way around [Geelen13]. Displaying an EC level viewpoint to all members of the EC motivates a collaborative sense of being a change agent in the members of the EC, triggering more community action to solve a problem. Jégou et al. use the example of a 'walking bus', wherein, parents took turns to walk children to school due to lack of safe transportation facilities [Jégou08]. To translate the 'walking bus' example, into an energy context, communities can self-organize to activate the desired flexibility to avoid congestion problems. The authors state that a community's ability to engage in bottom-up self-organization to solve problems also called *social innovation* is often more effective than top-down processes. Combining the research on the optimal design of user feedback with the research into the effectiveness of social innovation in self-organizing communities provides a strong framework for research into optimal energy modii user interaction. Designing messages that are at the same interaction level as the task level and involving the user at the EC level are two critical inferences for successful user interaction.

Within SUSTENANCE, initial work in the direction of building user interfaces and incorporating energy modii messages has begun. Figure 6.4 shows an example UI that would be used by the inhabitants of the EC. The production and consumption profiles can incorporate the energy modii. The UI can inform the users about when their profiles deviate from the desired Connected Energy Mode and list flexibility options to choose from. Upon choosing each option users may be shown a simulation of the effect of their decision. Users can then choose to go with the flexibility option that alleviates the undesired energy mode while minimizing loss of user comfort.

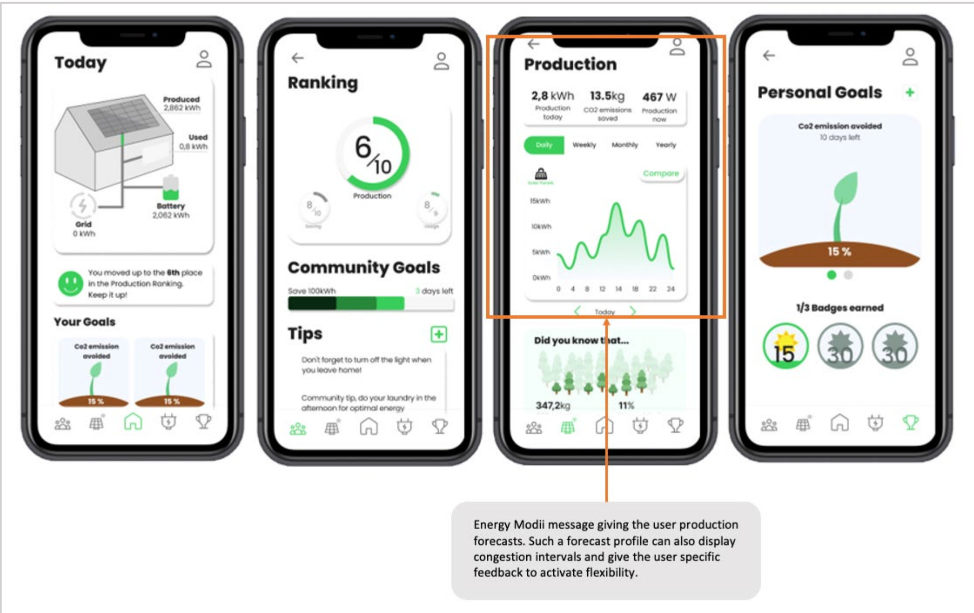


Figure 6.4: Snapshot of UI being developed for the EC and possible energy modii integration.

Similarly, Figure 6.5 shows the integration of energy modii messages into the UI app being developed for SlimPark users. Users are told that due to sudden cloud cover, the PV production will be lower than previously expected. This information allows the user to request a lower amount of charge for their EV. It is important to note that the UIs are currently under development. The intention of our future research is to incorporate the energy modii information from the signal and translate that into clear understandable messages for the user. Such messages could be accompanied with objective suggestions of how to activate flexibility to avoid undesired energy modii with the least compromise to user comfort.

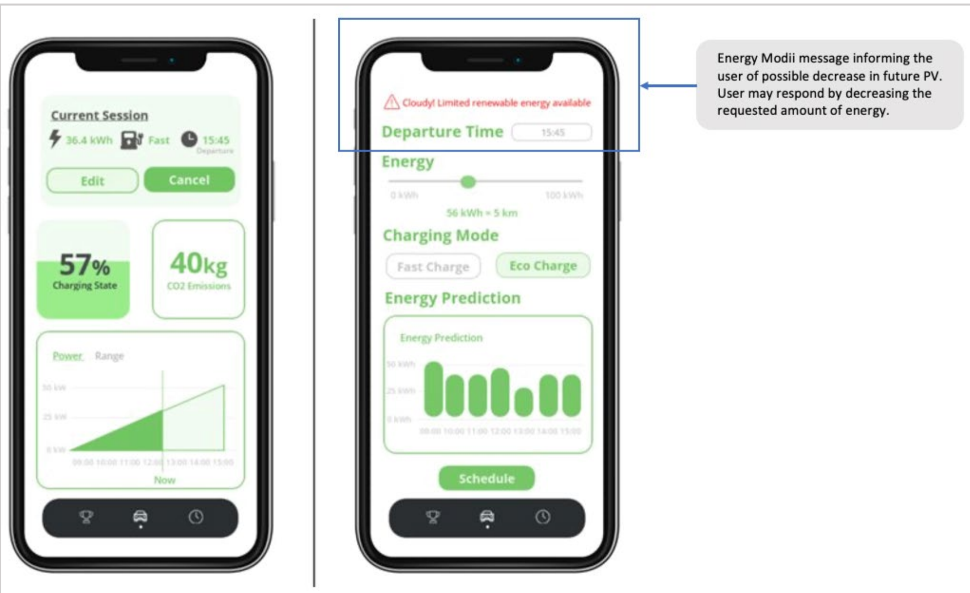


Figure 6.5: Snapshot of UI being developed for SlimPark and possible energy modii integration.

7 Evaluation

7.1 *Vriendenerf Demonstrator*

Following the methodology in Chapter 4, a DEMKit model was created for the 13 houses in the Vriendenerf EC. Each of the 12 residential dwellings were allotted an EV with 42 kWh capacity and 7kW charging power. The 13th dwelling is a common house (non-residential) and was not allotted an EV. All 13 dwellings were allotted a battery with 10kWh capacity and 10kW charging rate (1C) and a 150 L buffer tank. Lastly each of the 12 dwellings were assigned 23 PV panels and the common house was assigned 14 panels mirroring on-site information. These are the base parameters of our simulation and are illustrated in Table 7.1.

Table 7.1: Model parameters for Vriendenerf baseline model simulation.

EV	12 houses have EV EV with 42 kWh capacity, 7 kW charging power for each house. Common house (13th dwelling) not assigned an EV
Battery	All 13 dwellings have a battery Battery capacity 10kWh per house 1C Rate – charging power 10kW
Heatpump	150 L buffer tank per house
PV	23 panels per house, 260 Wp each = 5.98 kWp total for 12 houses 14 panels for common house, 260 Wp each = 3.64 kWp 0.975 inverter efficiency.

7.1.1 Base simulation and setting congestion limit

We begin by simulating the first 7 days of January with 50% of the dwelling battery capacity allotted to the PS algorithm (Figure 7.1). This means 50% of the 10kWh battery capacity per dwelling is controlled by the PS algorithm. The minimum power value (production) in Figure 7.1 (production) is -5.4 kW.

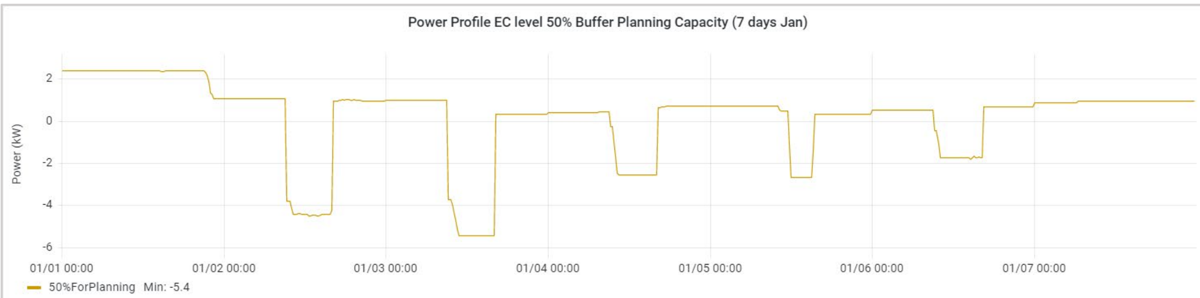


Figure 7.1: First 7 days of the Vriendenerf demonstrator DEMKit simulation

Using this simulation, we set a congestion limit of -4.4 kW, as illustrated in Figure 7.2. This leads to 2 instances where the planning crosses the negative congestion limit triggering the undesirable

Congestion Mode. These 2 instances are marked in Figure 7.2. Therefore, a congestion mitigation strategy needs to be activated to (re-)plan a power profile within the congestion limits.

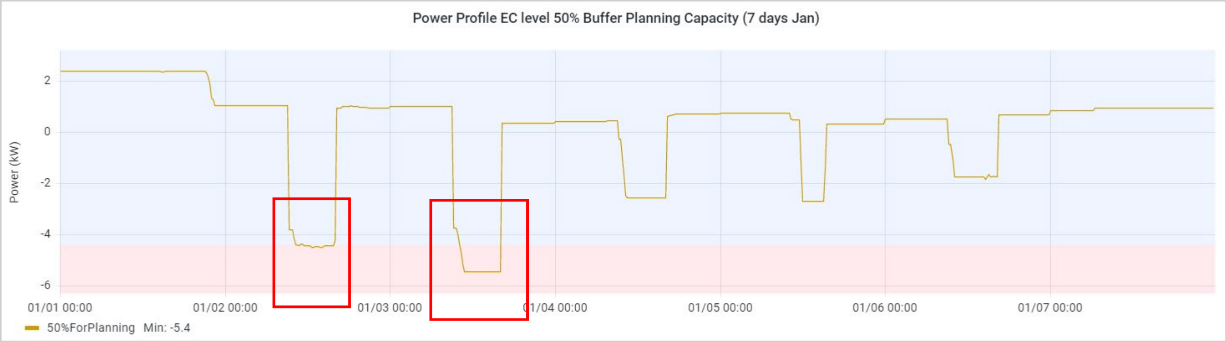


Figure 7.2: Congestion limit set to -4.4 kW. Red marks the undesirable Congestion Mode.

7.1.2 Congestion mitigation measure using buffer storage

The buffer storage is used to activate congestion mitigation measures in the Vriendenerf EC. Figure 7.3 illustrates simulations for the 7 day period but with 75% buffer capacity allotted to the PS algorithm. Allotting 75% buffer planning capacity to the PS algorithm mitigates the first congestion point bringing the power profile within the -4.4 kW limit. However, 75% buffer planning capacity reduces the second congestion point but is not enough to bring it within the -4.4 kW limit. Figure 7.4 shows the effect of increasing the buffer planning capacity to 90%. This allocates more planning capacity to the PS algorithm and mitigates the second congestion limit as well.

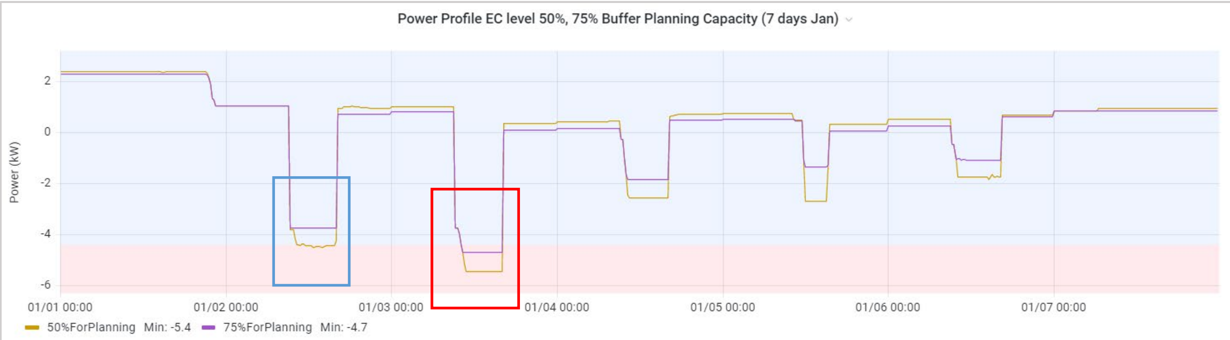


Figure 7.3: Changing 50% buffer planning capacity to 75% helps mitigate the first congestion point in the planning.

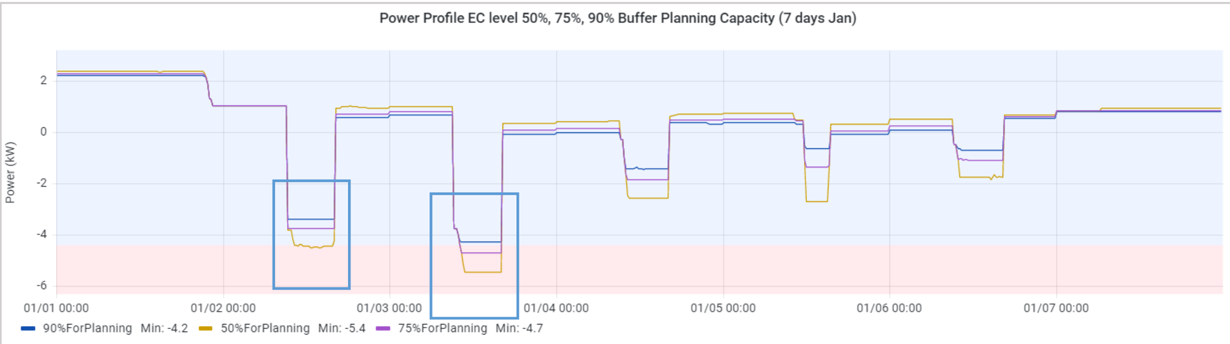


Figure 7.4: Increasing buffer capacity allotted to PS planning to 90% to mitigate the second congestion point.

Allotting more buffer capacity to the planning algorithm is an example of a congestion mitigation strategy. Such a strategy also agrees with the USEF “traffic-light’ model described in Chapter 4 (Grid Management: Figure 4.8). Mitigation strategies execute a base planning and then use the planning to discover upcoming congestion points (Green Mode> Yellow Mode). Thereafter the EC group controller activates measures of increasing strictness and calculates a new planning. Here the “increasing strictness” is illustrated with increasing buffer capacity allotted to the EC group controller. The EC controller checks which measure mitigates the congestion limit while having least effect on the user comfort (Yellow Mode > Green Mode). In case the EC group controller is unable to implement any measure to mitigate the congestion points successfully, then it may activate load shedding options (Orange Mode) as a final resort. However, the concept of energy modii allows for available flexibility in the EC to be used to create more options to mitigate undesirable modes before resorting to extreme measures such as forced curtailment.

7.2 University of Twente Field Lab “SlimPark”

7.2.1 Modelling

Similarly, to the approach described in Chapter 4, also a DEMKit simulation model was created for the University of Twente Field Lab “SlimPark”. This location houses 9 charging stations, 25 kWp PV panels, and a 30kWh battery. In this sense, the location differs substantially from residential areas often simulated with DEMKit. Therefore, the existing open-source example configuration is not applicable for this situation. Instead, a DEMKit simulation configuration was created from scratch, allowing us to also include code that makes the transition from simulation to practice seamlessly using digital twin principles.

On the basis, this model consists of a *Simulation* module, that takes care of the orchestration of all components and time synchronization. Upon transition to the real-world demonstrator, this component is replaced with the *Demonstrator* module. Essentially, this means that time synchronization with the hardware clock of the computer is enabled, but the execution model remains the same.

Next, all physical components are added to the model, being the charging stations, PV panels, battery, and grid connection. For these components, the base classes existing in the DEMKit component library are used. For simulation, 2 additional datasets need to be imported:

1. Firstly, historical data concerning the solar irradiation for the Twenthe weather station, as recorded by the Dutch metheorogical institute KNMI [WebKNMI], is imported. This is used to determine the solar yield given the orientation of the PV panels.
2. Secondly, EV charging patterns are required. These come in the form of constraints describing the arrival and departure time, and the total energy that should be charged in that time frame. Next to this, an EV type is required to assess how much power this car can charge and whether this concerns single-phase or three-phase AC charging [WebOpenEV]. Normally, such data is generated by the ALPG, but those patterns reflect at home charging. Instead, to populate the model with driving behaviour, we generated this data using the open-source EV Charging Demand generator (EVCDgen) [WebEgen, Nijenhuis22Emob]. This generator generates patterns by sampling sessions based on usage distributions resulting from surveyed driving patterns of Dutch citizens [CBS20].

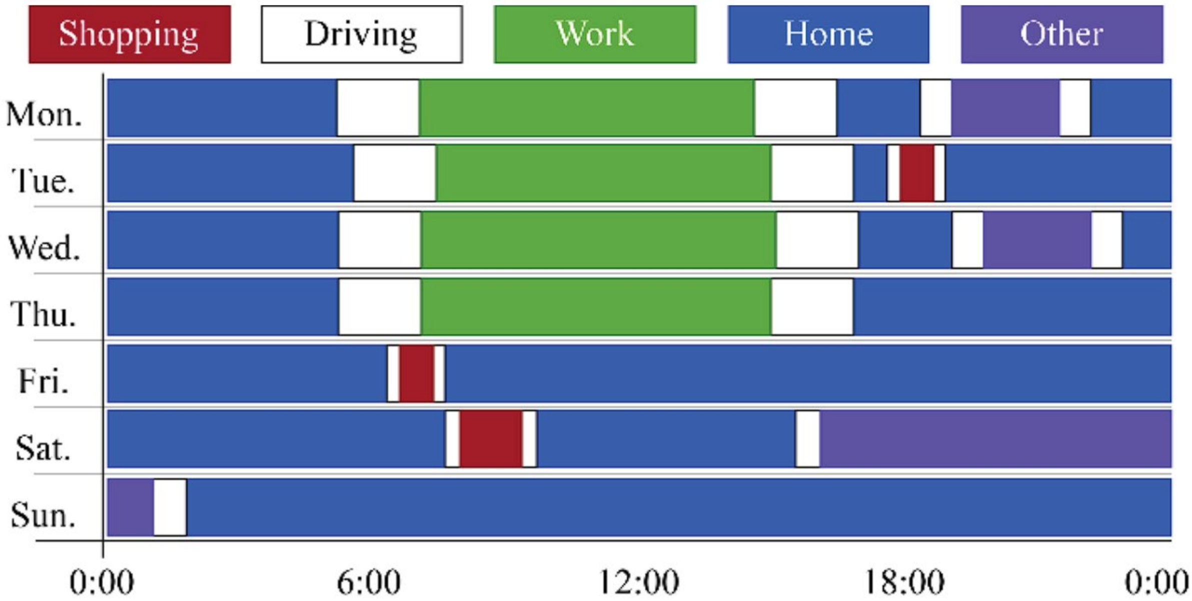


Figure 7.5: A possible EV connection pattern generated by EVDCgen [Nijenhuis22Emob]

A cyber part is put on top of this physical model, which reflects the control system. A simple hierarchical system is modelled using the Profile Steering method. Here, a *GroupController* is at the root of the control tree and represents the overall EMS that is in charge of the parking lot to ensure the power limit of the connection is not violated. Individual device controllers (agents) are connected to this EMS to perform decentralized optimization of the individual chargers (on behalf of the connected user), monitoring and predicting PV yield, and control of the battery. More specifically, we utilize the event-driven profile steering concept [Hoog17Async] in order to dynamically integrate the user input from the app upon their arrival. Hence, we simulate the use-case in an online fashion without perfect foresight.

7.2.2 GridShield

In collaboration with the Dutch organization on EV charging ElaadNL, founded by all Dutch DSOs together, we are using the University of Twente Field Lab as one of the test-sites for the so-called GridShield module [Nijenhuis22]. This module monitors the loading of the local grid and autonomously sends a command to charging stations to reduce their power in case of an overload. Simulation models of the GridShield system are developed for DEMKit [Tangerding22] and are included as optional model in our simulation model of SlimPark. The implementation of GridShield allows us to investigate the impact of a possible implementation of the grid congestion energy mode as described in Chapter 5.

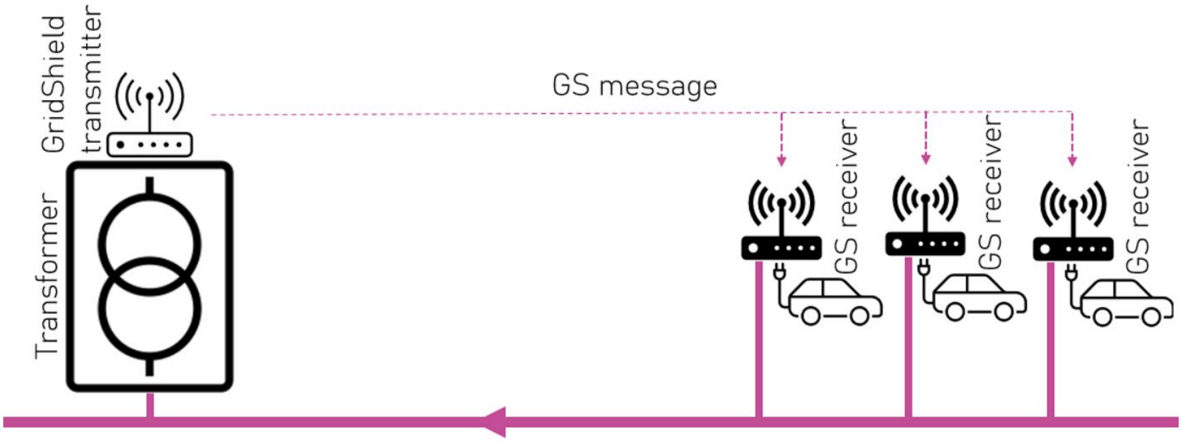


Figure 7.6: GridShield communication principle [Tang22]

7.2.3 Feeding back data from practice

The digital twin allows us to feed-back data from the live operating DEMKit instance at SlimPark for further analysis of the control and optimization algorithms. The used components in the UT Field Lab are chosen such that open machine communication interfaces are available. As a result, real measurement data from the charging stations, PV inverter, battery, and grid meter can be imported through a Modbus TCP interface. The charging stations are operated using the open-source charge point operator back-end SteVe [WebSteVe]. With the latter, exact arrival times, departure times, energy charged and the user can be retrieved. Subsequently, this can be fed back to the developed DEMKit model to refine control algorithms or test different strategies.

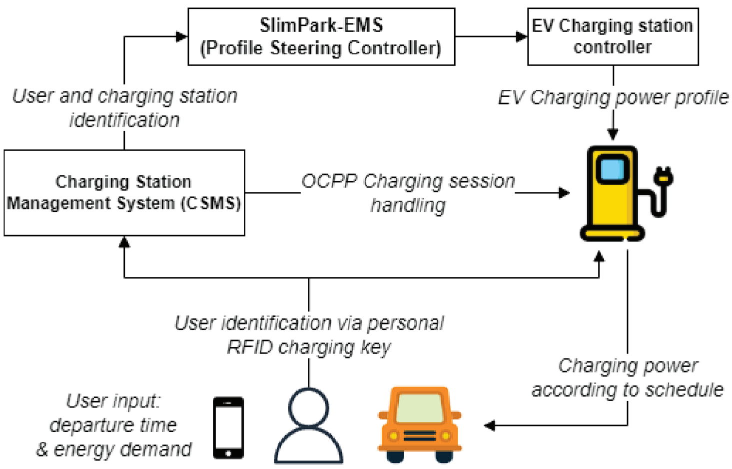


Figure 7.7: SlimPark demonstrator data and control flow schematic [Nijenhuis22]

7.2.4 University of Twente Field Lab results

7.2.4.1 Initial simulation study

Upfront, simulations are performed to yield insight in the resulting power profiles for different configurations. The modular model approach allows us to investigate the added value of smart EV charging control and the implementation of a battery storage system in this demonstrator. The results are depicted in Figure 7.8. From this simulation, which covers a workweek, it is clear that there is a huge potential for smart charging by aligning the charging with production of local energy using control. This will benefit the self-sufficiency of the parking lot, reduce the carbon emissions and significantly contribute to grid load minimization. The added value of a battery is very limited. However, the latter is included in the demonstrator for experimental purposes.

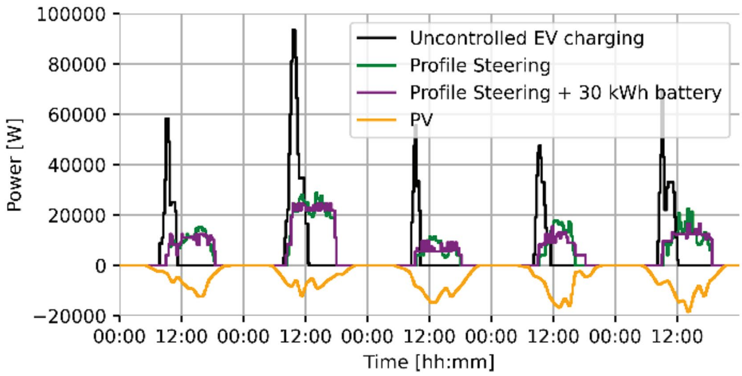


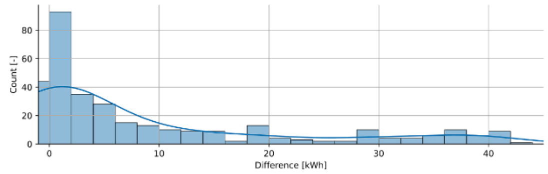
Figure 7.8: SlimPark simulation study [Nijenhuis22]

Note that sizing of solar panels is not considered in this case. The rooftop of SlimPark covers all 9 parking spots equipped with a charger. The 25kWp capacity will roughly translate in 25MWh of electricity production annually. This setup will therefore produce approximately 150.000 sustainable kilometres with a driving efficiency of 6km per kWh. This translates into 16.7k km per parking spot per year. This is significantly more than the average annual 11k km per Dutch car [WebCBSauto].

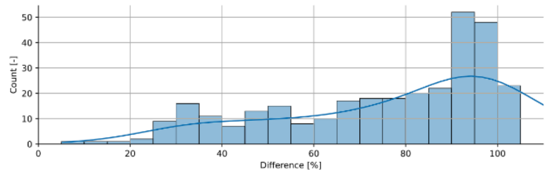
7.2.4.2 Digital-twin analysis using real data

The UT Field Lab has been operational for about a year the moment of writing. This means that already some data is collected in the demonstrator, which can be fed back into the DEMKit digital twin simulation environment. Data has been collected in two stages: (i) passive data collection without the EMS being enabled, and (ii) user interaction using the smart charging app with the EMS enabled. In this subsection we analyse initial user behaviour with the app (Chapter 5) and the effect of the EMS in order to reduce the carbon emissions through enhanced self-consumption.

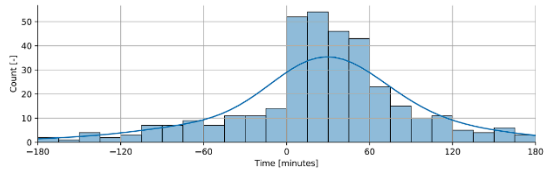
Analysis of the user behaviour since the introduction of the app shows that many users have inaccurate insight in their car and driving patterns. As can be expected, the departure time is often set a bit too early (Figure 7.9c), leaving some slack for an unexpected early departure whilst making sure that the car is still filled up. Often, users tend to set their departure time about half an hour before actual departure as retrieved from the charge system back-end. The total energy demand was initially overestimated with approximately 44%. This means that the users "order" 44% more energy than they charged. However, through the feedback in the app, the users learned their driving patterns and required energy. In the third month after introduction of the app, the overestimates dropped to 33%. The histogram of ordered energy is shown in Fig 7.9b).



(a) Histogram of the difference between the indicated energy demand and the actual energy delivered in kWh.



(b) Histogram of the delivered energy as a percentage of the scheduled energy demand.



(c) Histogram of the difference between the actual departure time and indicated departure time in minutes (0 being the indicated time by the user: a positive number means the user stayed longer than indicated).

Figure 7.9: Analysis of app input

Although the user estimates are far off from reality, the EMS is still able to utilize this data. In Figure 7.10 and Figure 7.11 we compare the average and worst-case loads on the grid for the period without control (01-01-2022 – 16-06-2022) and the period with control (13-6-2022 – 31-12-2022). It is clear that the peaks on the power grid have significantly reduced in the morning, before the sun is up. By shifting the charging, we also see a better utilization of the solar energy with less feed-in. We note that the period in which the app is utilized has more favourable periods for solar production.

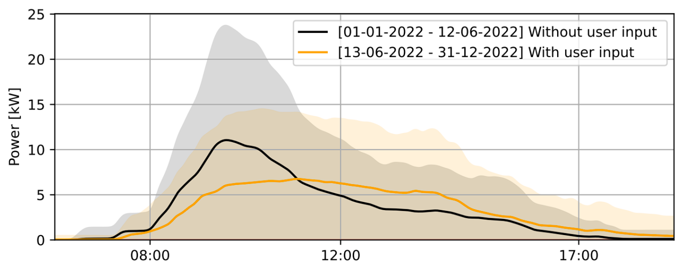


Figure 7.10: Mean and standard deviation of EV charging power for the working days in the indicated time periods.

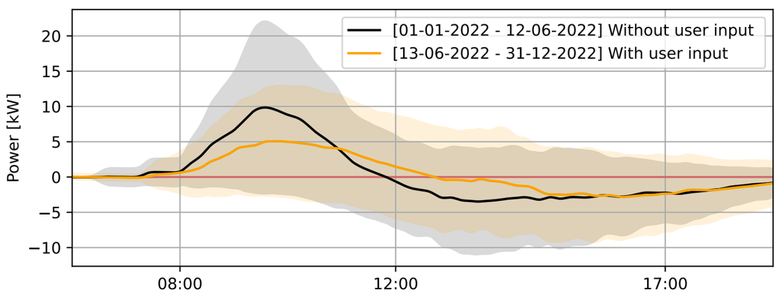


Figure 7.11: Mean and standard deviation of grid load (EV + PV) for the working

days in the indicated time periods

From the collected data, we can also perform comparative simulation studies in which the parameters are changed. We analyse 4 cases for the period in which the EMS is utilized:

- Business-as-usual: The standard charging in which the cars charge as quickly as possible from the moment they are connected;
- Measurements: The real-world obtained results;
- Event-based simulation: This simulates the same EMS, but now in the case that users provide correct information. This forms a practical lower limit of what would be possible with correct information;
- Perfect information simulation: This is an offline optimal schedule and forms a theoretical lower bound of what is possible.

Figure 7.12 below shows the resulting load duration curve for charging in the 800 load hours. Here it is clear that the smart charging solution (orange line) is significantly performing better then an uncontrolled case. However, it must also be noted that with better user input (green line) still significant improvements can be achieved.

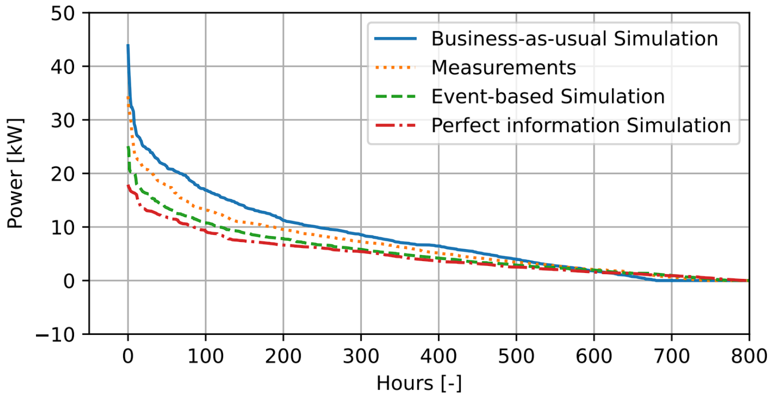


Figure 7.12: Load duration curve of simulations (based on real obtained data) with different controls.

Lastly, we look at the self-sufficiency of the UT Field Lab SlimPark, i.e., we look at how much of the used energy is produced locally by the PV system at the exact same time. The four different cases are compared and shown in Figure 7.13. Especially in the summer months we see a tremendous increase in the self-sufficiency through the introduction of the app. E.g., for June we see an increase from 33% to 71%. In general, we see about a doubling of self-sufficiency with the smart charging app. The other 2 simulations show again that there is room for improvement, but the gap with the more realistic event-based simulation is limited.

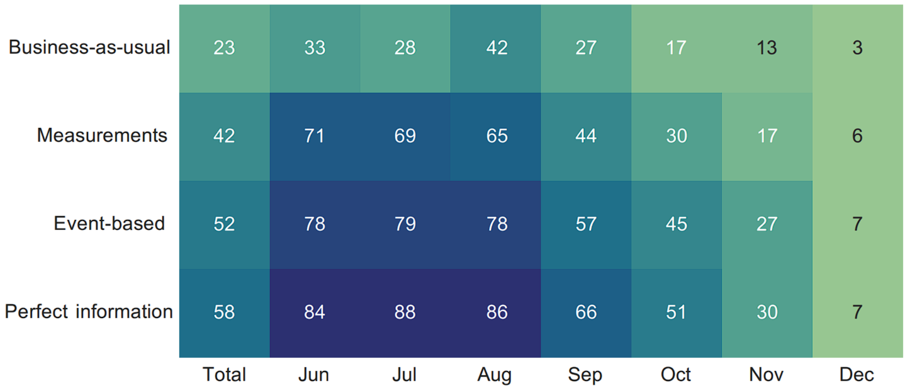


Figure 7.13: Self-sufficiency level heatmap in [%].

The results regarding the UT Field Lab show DEMKit's versatility to be utilized under different circumstances. Furthermore, the utilization of one code base in a digital-twin setting allows for various comparative simulation studies based on real-world data.

7.2.4.3 GridShield Congestion management

Lastly, an initial test was conducted with ElaadNL [vanSambeek23] in practice to test the impact of GridShield on system (see Figure 7.14). Here, 4 cars were charging in a controlled environment to create an overloading (congestion) condition that must be resolved. With the arrival of the fourth EV, the connection limit threshold is surpassed, and action is taken to first drop the power (between 14:01:10 and 14:01:45). Subsequently the power is slowly increased again. Note that EV2 is a single-phase charging EV and was unaffected due to its lower overall power.

One crucial observation in the testing of GridShield modules is that they overrule the EV charging power set by the EMS. However, the EMS is not aware of this and thus might use the freed-up capacity to e.g. charge the battery and still cause an overload. The developed energy modii in SUSTENANCE form a solid base for uniform communication to all smart grid systems to prevent such issues. Discussions with ElaadNL and Dutch DSOs are ongoing for standardization of control schemes for congestion mitigation in low voltage grids.

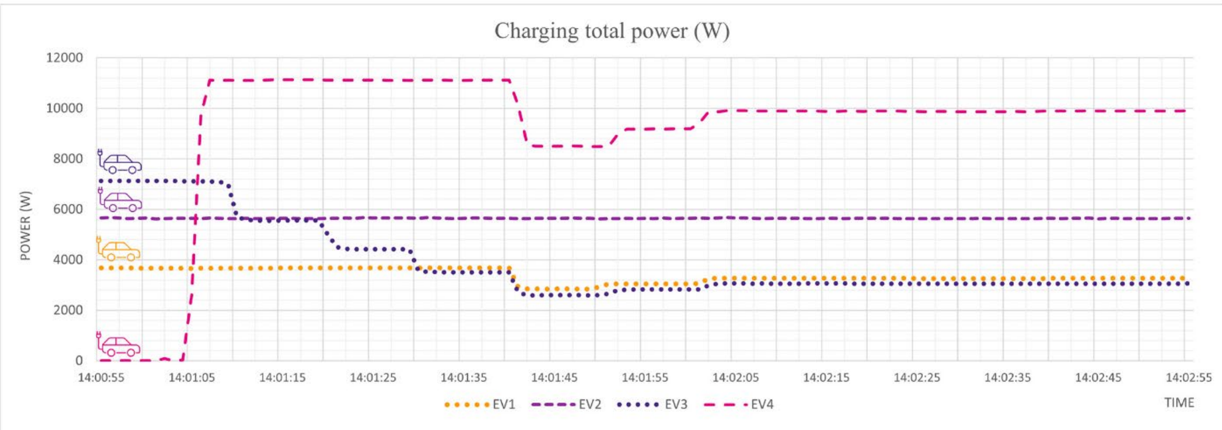


Figure 7.14: GridShield congestion management being triggered to avoid overloading (power is per phase) [vanSambeek23]

7.3 Aardehuizen Olst demonstrator

Lastly, we evaluate the proposed toolchain and method (see Chapter 4) on the significantly different Aardehuizen community. For the purpose of proving the suitability for reproducibility, we only consider the steps 1 to 3, i.e. we create and validate the base model.

Survey information, combined with public information [WebAard], personal communications, and publicly available statistics [WebCBSeng], is used as input for the ALPG configuration. A generation step with this configuration results in a load profiles in 1-minute resolution and flexibility information for each of the 24 houses, which in turn serves as input data for the DEMKit simulation model of the Aardehuizen neighbourhood. Within this model, per house information about the PV panels and inverter specifications and the electric boiler were added. The power profiles that result from simulations of a base-case, i.e. the situation as is currently, have been fine-tuned to match the collected information about the annual consumption at the Aardehuizen community

Figure 7.15 shows the total simulated power profile at the neighbourhood/community level and Figure 7.16 shows the total power profile of a smart meter installed in one of the houses for 1 week. Both the house and the time period of 1 week are randomly chosen from the provided dataset by one of the inhabitants. Power data with 15 minutes resolution was used for both graphs.

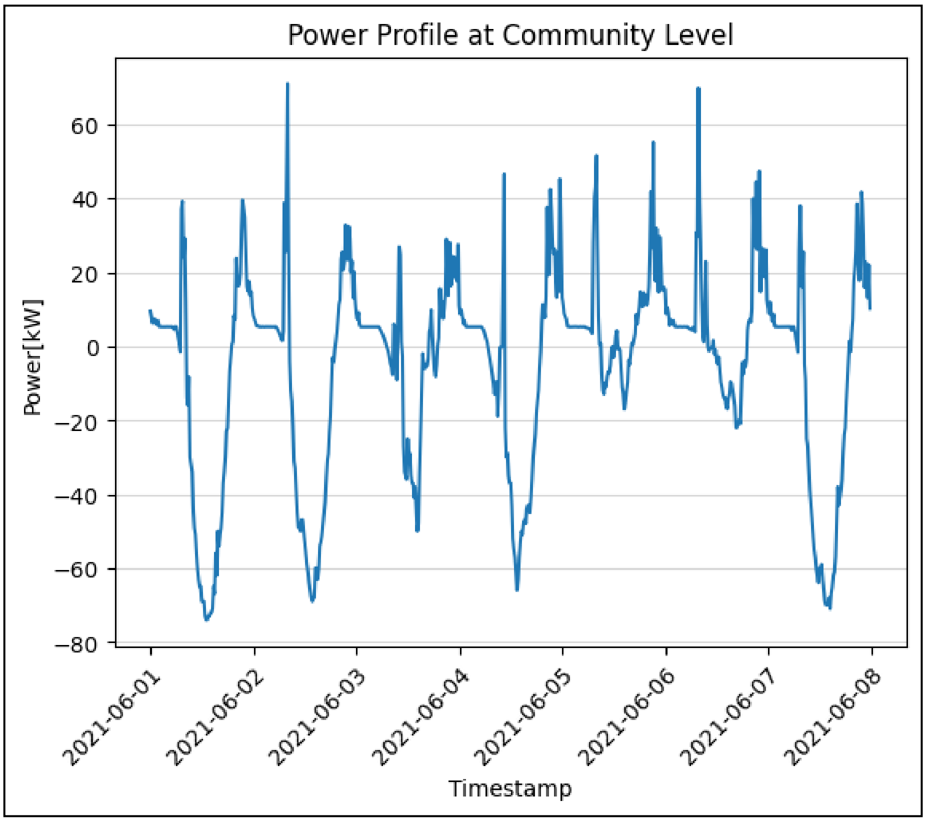


Figure 7.15: Power profile for 1 week at the neighbourhood community level.

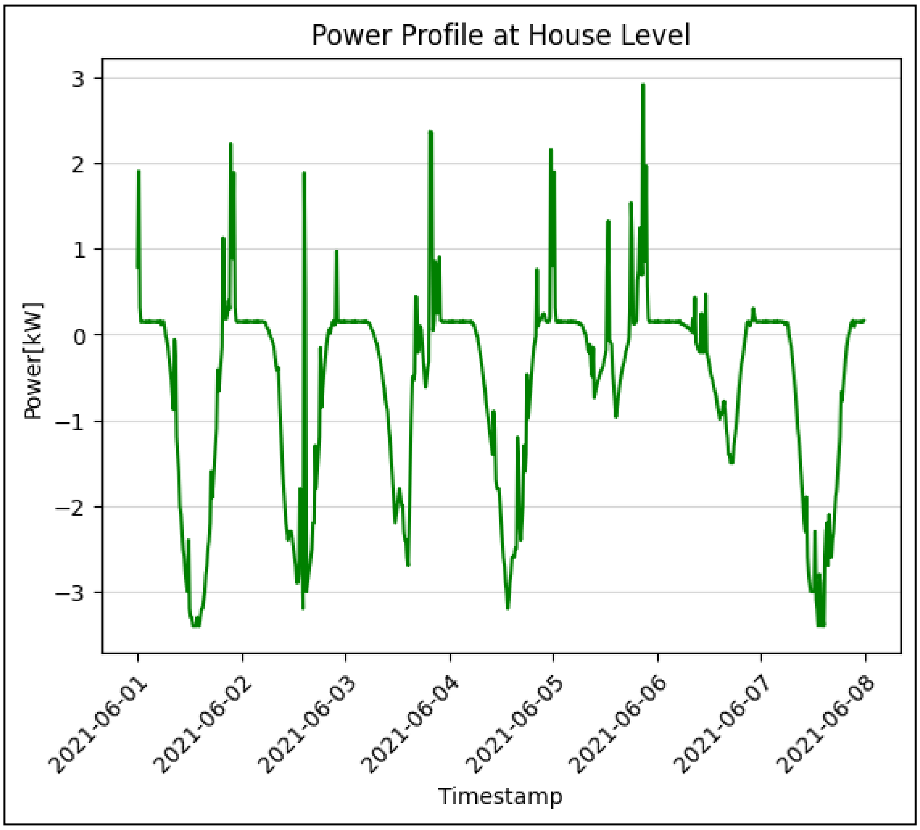


Figure 7.16: Power profile for 1 week at the house level.

The average annual energy consumption per house of Aardehuizen is approximately 1400kWh. This is based on the obtained survey data and recorded on-site smart meters. The average annual energy consumption per house of the Aardehuizen model in DEMKit is 1636 kWh. Therefore, the ALPG generated data shows a difference of 233 kWh with the on-site smart meter data.

This difference is still significant but can be attributed to many factors that are hard to model. For example, the ALPG assumes a regular energy usage for the community house. In reality, it can be expected that the complete different usage of this building also results in a significant different power profile. Furthermore, as indicated in the houses have significant different equipment than an average house, for which the ALPG was designed (such as the solar collectors and the design that minimizes heating usage). However, the difference is not too large as well. As such, the proposed methodology and toolchain allows experts to quickly setup a base model, even for vastly different energy communities.

For the Aardehuizen community, this means that additional modelling is required, for which components that model the various thermal systems and solar collectors exist in DEMKit. These elements can be manually added into the DEMKit model.

8 Conclusions

This deliverable has provided methods to model near smart controlled neighbourhoods with multi-energy systems. The presented DEMKit + ALPG toolchain allows experts to perform design space exploration to define near-autarkic neighbourhoods and investigate the combination of adding flexibility assets in conjunction with different energy management strategies. Next, energy modii have been theoretically defined and tested to unlock additional flexibility if needed to avoid outages in the power system due to electrification and the ongoing integration of RES.

8.1 Conclusions

Based on the presented contents, the research questions as introduced in Chapter 2 can be answered:

1. *How to model energy communities with flexible assets and subsequently evaluate different possible configurations with respect to autarky?*

For such an evaluation, it is key to have a modular modelling approach. Different possible configurations are a multi-dimensional aspect that includes: sizing of assets, energy management, and the interaction of users. Hence, it is key to not only model static power consumption, but also the flexibility. The latter is not only technical but relies mostly on the behavior of people. The DEMKit + ALPG toolchain provides these aspects.

2. *What possible internal and external circumstances have an effect on the energy system and its stability?*

External circumstances include geo-political situations that affect the price signals sent to the EC. They may also include grid issues such as a congestion during hours of peak demand or lack of enough supply from the external grid to fulfill the EC's energy demand. On the other hand, a mismatch in time between peak demand and peak production can be an internal EC problem. An example of an intra-day internal problem can be a sudden change in the planning, in terms of promised flexibility not delivered. For example, an electric vehicle that commits to being at the community charging point from 17:00 till 21:00, suddenly changes its plans and doesn't arrive at the community during the committed hours. This leads to a sudden lack of promised flexibility, that can affect the stability of the EC's energy system. In general, there are a multitude of circumstances that can affect the desired planning of an EC. These circumstances only increase with the increasing number of flexible devices added to the grid.

3. *Can these different circumstances be translated into a limited set of abstract parameters that define the different energy modii?*

External and internal circumstances, despite their variety and quantity, can be translated into more elementary basic grid variables which can be integrated into the planning signal of the EC. This allows for the state of the EC to be classified into finite mathematically formulated modes. In each mode, the information of the external or internal circumstance can be incorporated into the planning signal such that demand side management approaches are executed to balance the EC grid in a way that the undesirable effect can be mitigated with minimal loss to user comfort.

4. *How do these energy modii lead to different optimization objectives for energy management systems and the performance of a community with respect to autarky?*

Undesirable disturbances and changes to the energy grid can be translated into variables integrated into the planning signal. The finite scenarios thus created are called energy modii. Each mode of the EC generates a different planning signal that aims to use the flexibility of the EC in way that can aid the mitigation of an undesirable mode. This implies that the total available flexibility is conservatively used in the desirable mode. In the undesirable modes, a re-planning with the remaining flexibility can aid in exiting the undesirable mode. Being able to forecast modii and pro-actively altering the planning signal to account for the upcoming modii allows an EC to mitigate grid problems locally as well. This increases the autarky of the EC.

5. *How can these modii be effectively, clearly and transparently communicated to end-users in order for them to assist the energy system?*

The technical definitions allow for a uniform description of modii in terms of situation, precise limitations, and (if known) duration. These are essential aspects for algorithms to correctly anticipate. However, these clear definitions also make it easy to derive clear communication to end-users about the status of the grid. Furthermore, the use of the same definition allows algorithms to aid end-users, i.e., optimal results can be translated into concrete and clear tips on how end-users can help. This creates an accessible situation for end-users to assist both the EMS and the overall energy system stability.

8.2 Future work

The research conducted for this deliverable is already executed in DEMKit. Therefore, as explained for SlimPark, a solid basis for deployment in practice has been developed. The presented DEMKit model specifications form the input for the configuration files of the EMS in the demonstrators. For this, the DEMKit code will be deployed on the IECON IoT systems developed within SUSTENANCE. In the future we further develop the energy modii algorithms and utilize the real-world experience to further enhance the modii.

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